CECW-EI

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

Technical Letter
No. 1110-2-560

30 June 2001

EXPIRES 1 July 2006

Engineering and Design
RELIABILITY ANALYSIS OF NAVIGATION LOCK AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT

1. Purpose

This engineer technical letter (ETL) provides guidance for assessing the reliability of mechanical and electrical systems of navigation locks and dams and for establishing an engineering basis for major rehabilitation investment decisions. This cover letter defines terms and concepts associated with reliability analysis. Appendix B lists Web sites that contain information useful to reliability studies, Appendix C describes the acquisition of failure data, Appendix D gives an example reliability analysis for mechanical equipment, Appendix E gives an example reliability analysis for electrical equipment, Appendix F gives an example of lock and dam mission reliability, and Appendix G evaluates a non-series-parallel system.

2. Applicability

This ETL is applicable to all USACE Commands having Civil Works responsibilities. It applies to all studies for navigation lock and dam projects.

3. References

Publications are listed in Appendix A.

4. Distribution Statement

Approved for public release, distribution is unlimited.

5. Background

a. Navigation lock and dam facilities are an important link in the Nation's transportation system. Their mission is to maintain the navigable waterways and allow both cargo transport and recreational traffic between adjacent segments of the waterways. The mechanical and electrical components at these facilities function as systems to operate the various gates and valves. Breakdowns and poor performance of these systems can cause delays to navigation and adversely affect the overall national economy.

b. Lock and dam major rehabilitation projects began being budgeted under the Construction, General, and Flood Control, Mississippi River and Tributaries appropriation account in Fiscal Year

This ETL supersedes ETL 1110-2-549 dated 30 November 1997.

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(FY) 1993. To qualify as major rehabilitation projects, the work activities must extend over two full construction seasons and the total required implementation costs must be greater than a certain minimum threshold. The threshold amounts are adjusted annually for inflation as published in the Army Programs – Corps of Engineers Civil Works Direct Program – Program Development Guidance. To compete successfully as new starts, major rehabilitation proposals must be supported by the same level of economic analysis as new water resource projects. Chapter 3 of Engineer Regulation (ER) 1130-2-500 establishes policy for major rehabilitation at completed Corps projects. Chapter 3 of Engineer Pamphlet (EP) 1130-2-500 establishes guidance for the preparation and submission of Major Rehabilitation Project Evaluation reports for annual program and budget submissions.

c. The rehabilitation of mechanical and electrical equipment is usually included as part of the overall project. Rehabilitation may include replacement and/or reconditioning to restore or improve a system to a like-new condition. The rehabilitation may be considered from various perspectives. It may be necessary to restore existing equipment that has deteriorated with time or failed in service; or equipment may become obsolete, and replacement might be desired to upgrade the equipment to modern standards. The Major Rehabilitation Evaluation reports and supporting information will have to provide evidence of criticality with a certain level of detail based on specific uniform engineering criteria. Reliability assessments based on probabilistic methods provide more consistent results and reflect both the condition of existing equipment and the basis for design.

d. Further guidance for the reliability evaluation of hydropower equipment has been published in ETL 1110-2-550 and Mlakar 1994.

6. Reliability Concepts and Definition of Terms

a. Definition of terms.

(1) *Component.* A piece of equipment or portion of a system viewed as an independent entity for evaluation, i.e., its reliability does not influence the reliability of another component.

(2) *System.* An orderly arrangement of components that interact among themselves and with external components, other systems, and human operators to perform some intended function.

(3) *Failure.* Any trouble with a component that causes unsatisfactory performance of the system.

(4) *Hazard function or failure rate.* The instantaneous conditional probability of failure of an item in the next unit of time given that it has survived up to that time. It is the mean number of failures of a component per unit exposure time.

(5) *Reliability.* The probability that an item will perform its intended function under stated conditions, for either a specified interval or over its useful life.

(6) *Basic reliability.* Measure of the demand for maintenance and logistic support of a system caused by unreliability.

(7) *Mission reliability.* Measure of operational effectiveness of a system. A mission reliability prediction estimates the probability that items will perform their required functions during a mission.

(8) *Unsatisfactory performance.* Substandard operation; partial or complete shutdown of the system; operation of safety devices; unexpected deenergization of any process or equipment.

b. Measures of component reliability.

(1) *Reliability function.* The continuous probabilistic approach to item reliability is represented by the reliability function. It is simply the probability that an item has survived to time t. The mathematical expression can be summarized by

$$R(t) = P(T \geq t) \tag{1}$$

where

$R(t)$ = reliability of the item, i.e., probability of success

$P(T \geq t)$ = probability that the time to failure of an item will be greater than or equal to its service time

T = time to item failure

t = the designated period of time for the operation of the item

Conversely, the probability of failure $F(t)$ is simply

$$F(t) = 1 - R(t) \tag{2}$$

(2) *Hazard function or failure rate.*

(a) The failure rate or hazard function $h(t)$ represents the proneness to failure of a component as a function of its age or time in operation. It reflects how the reliability of a component changes with time as a result of various factors such as the environment, maintenance, loading, and operating condition. From Modarres (1993) it can be shown that

$$f(t) = \frac{-dR(t)}{dt} \tag{3}$$

$$h(t) = \frac{f(t)}{R(t)} \tag{4}$$

where $f(t)$ is the probability density function (pdf). This is a mathematical description for the curve approximation of the number of the probable occurrences of a specific random variable (i.e., the failure of a component for use in this ETL).

(b) The hazard function or instantaneous failure rate is the instantaneous conditional probability of failure of an item in the next unit of time given that it has survived up to that time. The hazard function can increase, decrease, or remain constant. It has been shown that the failure rate behavior of most mechanical and electrical engineering devices follows that shown in Figure 1. This is known as the *bathtub curve*. Region A represents a high initial failure rate, which decreases with time to nearly constant. This is known as the infant mortality region and is a result of poor workmanship or quality control. Region B represents the useful life phase. Here, failures occur because of random events. Region C represents the wear-out phase where failures occur due to complex aging or deterioration.

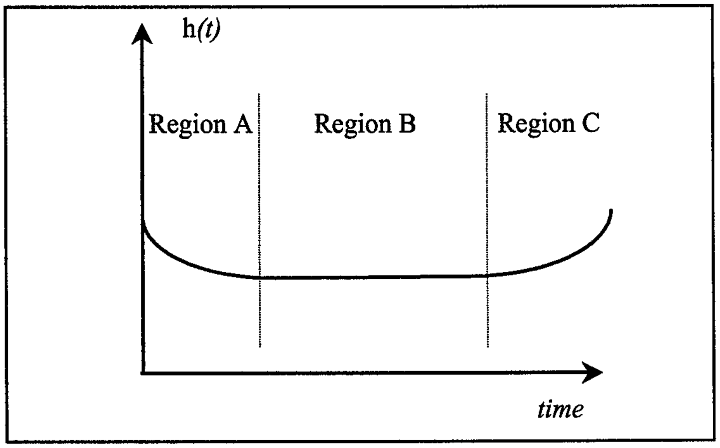


Figure 1. Typical bathtub curve

(c) The flat random or chance failure region (Region B) of the curve for electromechanical devices is much longer than the other two regions. Electrical devices exhibit a much longer chance failure period than mechanical devices. Methods presented in this ETL will attempt to determine reliability and predict the characteristics of Regions B and C of the bathtub curve for mature equipment using the common continuous distribution functions discussed in the next paragraphs. The infant mortality region (Region A) will not be directly discussed in this ETL since the equipment considered for major rehabilitation projects usually falls into Regions B or C.

(3) *Exponential distribution.*

(a) The exponential distribution is the most commonly used distribution used in reliability analysis. The reliability function is

$$R(t) = e^{-\lambda t} \tag{5}$$

where

t = time

λ = failure rate

This distribution can be used to represent the constant hazard rate region (Region B) of the bathtub curve. The hazard function for the exponential distribution remains constant over time and is represented as simply λ:

$$h(t) = \lambda \tag{6}$$

Plots of the reliability and hazard functions for the exponential distribution are shown in Figures 2 and 3, respectively.

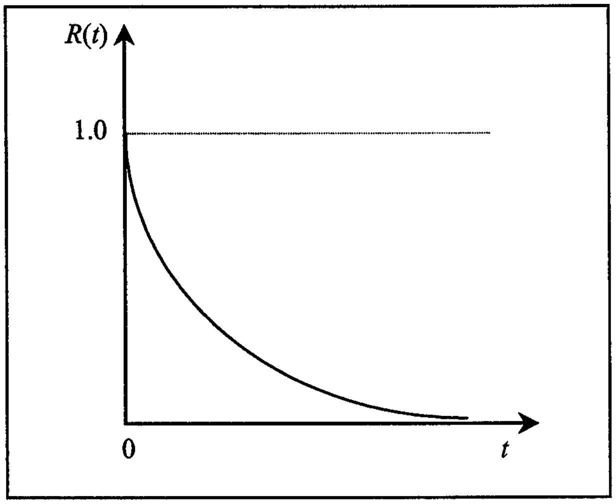


Figure 2. Reliability function for exponential distribution

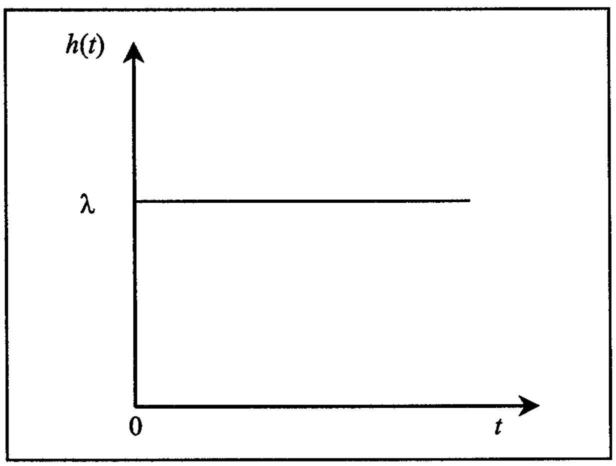


Figure 3. Hazard function for exponential distribution

(b) The average or mean of the exponential life distribution is the Mean Time to Failure (MTTF). It is the average length of life of all units in the population. It has significance in that the reciprocal of the hazard rate is equal to the MTTF:

$$\mathrm{MTTF} = \frac{1}{\lambda} \tag{7}$$

(4) *Weibull distribution.* The Weibull distribution is a generalization of the exponential distribution. This distribution covers a variety of shapes, and its flexibility is useful for representing all three regions of the bathtub curve. The Weibull distribution is appropriate for a system or complex component made up of several parts. The Weibull reliability function is

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{8}$$

where

α = the scale parameter or characteristic life

β = the shape parameter

For $0 < \beta < 1$, the Weibull distribution characterizes wear-in or early failures. For $\beta = 1$, the Weibull distribution reduces to the exponential distribution. For $1 < \beta < \infty$, the Weibull distribution characterizes the wear-out characteristics of a component (increasing hazard rate). The Weibull hazard function is

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{9}$$

Plots of the reliability and hazard functions for the Weibull distribution are shown in Figures 4 and 5, respectively.

c. General data required. Reliability analysis provides the best estimate of the reliability anticipated from a given design within the data limitations and to the extent of item definitions. The required data are dependent on the availability and depth of analysis required. Mechanical and electrical components are typically complex and made up of many different parts, each with several modes of failure. These failure modes are associated with many ambiguous variables such as operating environment, lubrication, corrosion, and wear. Historic data for lock and dam equipment have not usually been available. Lock and dam equipment for which data are not available requires the analysis to be completed using data from larger systematic samples of similar equipment such as the published failure rate data in Reliability Analysis Center (1995). Failure rate data can also be obtained by multivariate methods developed in Naval Surface Warfare Center (1992). Prior to any reliability determination, investigations should be conducted to gain a thorough knowledge of the mechanical and electrical requirements and layouts, to identify equipment deficiencies, and learn the project history and future demands.

d. Internet Web site. An Internet Web site (Appendix B) has been established as a means to collect both historical and recent failure data for lock and dam mechanical and electrical equipment. It is intended that the data will be continually collected and compiled so that accurate failure rate tables can be developed. The data will better represent lock and dam equipment. The most important benefit is that the most current failure data for Corps mechanical and electrical equipment will be available to engineers doing the reliability work for future projects. In addition, it will provide a central reference source for operations and engineering personnel to check when failures occur to see if there are common problems with installed equipment. The most current data has been included in Appendix C. Engineering and operations personnel are encouraged to input available failure data. The Web site should be checked for the latest failure rate data when a reliability analysis is being developed.

7. Engineering Reliability Analysis

Assessment of the reliability of a system from its basic elements is one of the most important aspects of reliability analysis. As defined, a system consists of a collection of items (components, units, etc.) whose

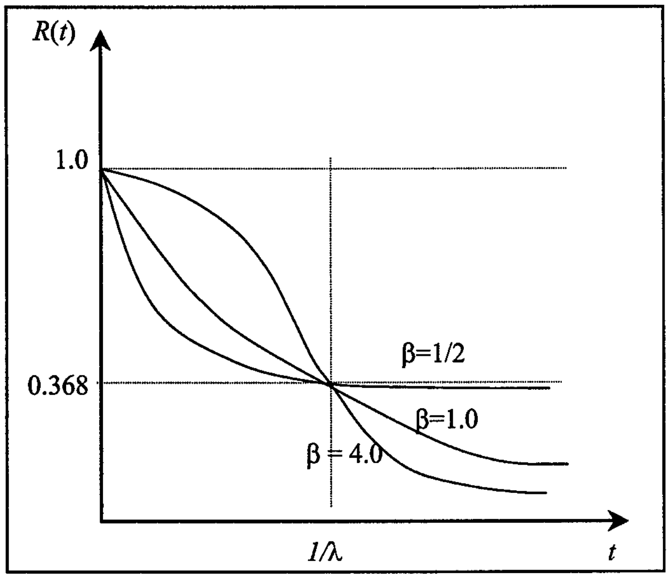


Figure 4. Reliability function for Weibull distribution

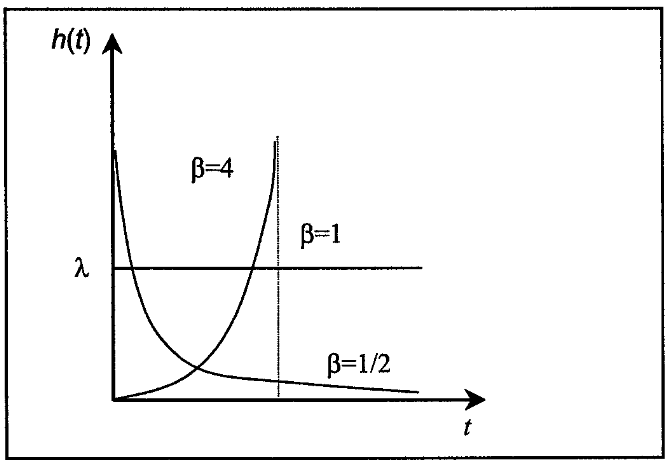


Figure 5. Hazard function for Weibull distribution

proper, coordinated function leads to its proper operation. In reliability analysis, it is therefore important to model the reliability of the individual items as well as the relationship between the various items to determine the reliability of the system as a whole. This ETL applies the reliability block diagram (RBD) method as outlined in MIL-STD-756B to model conventional probability relationships of collections of *independent* components and systems.

8. System Reduction

The number of discrete mechanical and electrical components in a lock and dam requires system reduction to reduce the vast complexity of numerous components into smaller groups of critical components. The reliability models should be developed to the level of detail for which information is available and for which failure rate (or equivalent) data can be applied. Functional elements not included in the mission reliability model shall be documented, and rationale for their exclusion shall be provided.

9. Component Reliability

The failure distribution appropriate to the specific electronic, electrical, electromechanical, and mechanical items should be used in computing the component reliability. In most cases, the failure distribution will not be known and the exponential or the Weibull may be assumed. The α and β parameters of the Weibull equation are normally empirically determined from controlled test data or field failure data. This ETL presents a procedure for estimating these values. If the β value in the Weibull function is unknown, a value of 1.0 should be assumed. The flat failure region of mechanical and electrical components is often much longer than the other two regions, allowing this assumption to be adequate. Once the component reliability values are determined, the RBD method is used to evaluate their relationship within the system to determine the total system reliability. Appendices D and E contain more information on determining component reliability. In Appendix F, the mechanical and electrical subsystem reliability data from Appendixes D and E are applied to the overall system to determine an overall lock and dam system mechanical and electrical reliability value.

10. System Risk Analysis Using Block Diagrams

The necessity for determining the reliability of a system requires that the reliability be considered from two perspectives, basic reliability and mission reliability. Both are separate but companion products that are essential to quantify the reliability of a system adequately. The incorporation of redundancies and alternate modes of operation to improve mission reliability invariably decreases basic reliability. A decrease in basic reliability increases the demand for maintenance and support. Basic reliability is normally applied to evaluate competing design alternatives.

a. Basic reliability - Series System Model. A basic reliability prediction is a simplified model that is intended to measure overall system reliability. It is used to measure the maintenance and logistic support burden required by the system. A basic reliability model is an all-series model. Accordingly, all elements providing redundancy or parallel modes of operation are modeled in series. In a series system, the components are connected in such a manner that if any one of the components fails, the entire system fails. Care should be taken when developing this type of model since the final value of the basic reliability of the system is inversely proportional to the number of components included in the evaluation; i.e., the more components there are, the lower the reliability. Such a system can be schematically represented by an RBD as shown in Figure 6.

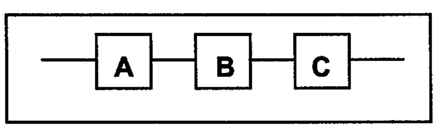


Figure 6. Series system

For a system with N mutually *independent* components, the system reliability for time t is

$$R_S(t) = R_A(t)*R_B(t)*R_C(t)*\ldots* R_N(t) \tag{10}$$

It can also be shown that if $h_s(t)$ represents the hazard rate of the system, then

$$h_s(t) = \sum_{i=1}^{n} h_i(t) \tag{11}$$

The failure rate of a series system is equal to the sum of the failure rates of its components. This is true regardless of the failure distributions of the components.

b. Mission reliability. The mission reliability model uses the actual system configuration to measure the system capability to successfully accomplish mission objectives. The mission reliability model may be series, parallel, standby redundant, or complex.

(1) *Parallel system model.* In a parallel system, the system fails only when all of the components fail. Such a system is represented in Figure 7. In this configuration, the system will still perform if at least one of the components is working.

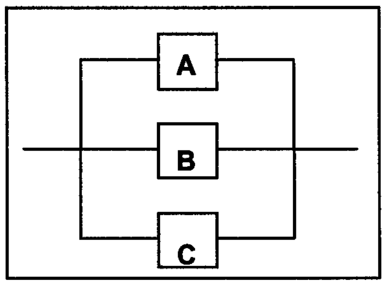


Figure 7. Parallel System

The reliability for the system is given by

$$R_S(t) = 1 - [1 - R_A(t)][1 - R_B(t)][1 - R_C(t)] \tag{12}$$

or,

$$R_S(t) = 1 - \prod_{i=1}^{N} [1 - R_i(t)] \tag{13}$$

A more general form of a parallel system is the "*r* out of *n*" system. In this type of system, if any combination of *r* units out of *n independent* units arranged in parallel work, it guarantees the success of the system. If all units are *identical*, which is often the case, the reliability of the system is a binomial summation represented by

$$R_S(t) = \sum_{j=r}^{n} \binom{n}{j} R(t)^j [1 - R(t)]^{n-j} \tag{14}$$

where

$$\binom{n}{j} = \frac{n!}{j!(n-j)!} \tag{15}$$

The hazard rate for parallel systems can be determined by using

$$h_s(t) = \frac{-\mathrm{d}\, ln\, R_s(t)}{dt} \tag{16}$$

or

$$h_s(t) = \frac{-\mathrm{d}\, ln \left\{1 - \prod_{i=1}^{N} [1 - R_i(t)]\right\}}{dt} \tag{17}$$

The result of $h_s(t)$ becomes rather complex and the reader is referred to the reference literature.

(2) *Standby redundant system.* A two-component standby redundant system is shown in Figure 8. This system contains equipment that is in primary use and also equipment standing idle ready to be used. Upon failure of the primary equipment, the equipment standing idle is immediately put into service and switchover is made by a manual or automatic switching device (SS).

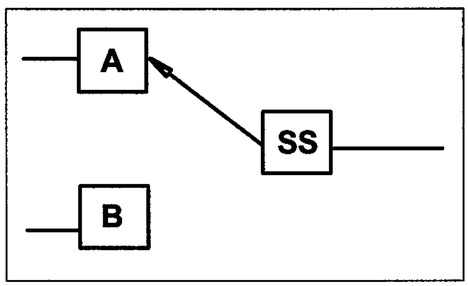


Figure 8. Standby redundant system

The system reliability function for the exponential distribution can be calculated for a two-component, standby redundant system using the following equation:

$$R_S(t) = R_A(t) + \frac{[\lambda_A R_B(t)]}{\left(\lambda_A + \lambda_{SS} + \lambda_B' - \lambda_B\right)} \left\{1 - exp[-\left(\lambda_A + \lambda_{SS} + \lambda_B' - \lambda_B\right) d_i t]\right\} \tag{18}$$

where

λ_A = hazard rate of A

λ_{SS} = hazard rate of switching device

λ_B' = hazard rate of the standby equipment while not in use

λ_B = hazard rate of B

d_i = duty factor for respective failure rate

(3) *Complex system models.* Complex systems can be represented as a series-parallel combination or a non-series-parallel configuration. A series-parallel RBD is shown in Figure 9. This type of system is analyzed by breaking it down into its basic parallel and series modules and then determining the reliability function for each module separately. The process can be continued until a reliability function for the entire system is determined. The reliability function of Figure 9 would be evaluated as follows:

$$R_1(t) = (1 - \{[1 - R_{A1}(t)]\,[1 - R_{B1}(t)]\,[1 - R_{C1}(t)]\}) * R_{D1}(t) \quad (19)$$

$$R_2(t) = (1 - \{[1 - R_{A2}(t)]\,[1 - R_{B2}(t)]\}) * R_{D2}(t) \quad (20)$$

$$R_S(t) = (1 - \{[1 - R_1(t)]\,[1 - R_2(t)]\}) \quad (21)$$

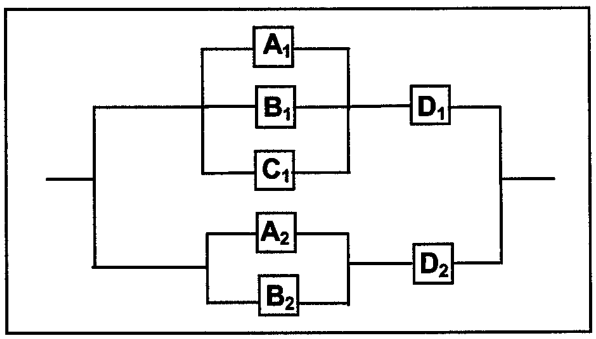


Figure 9. Series-parallel system

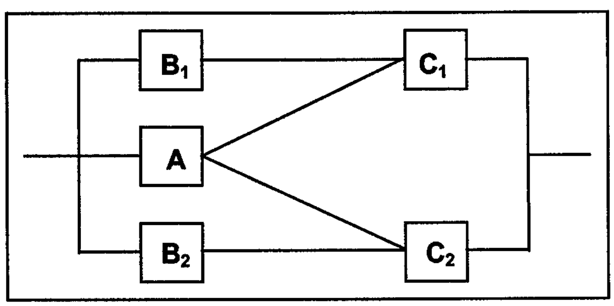


Figure 10. Non-series-parallel system

A non-series-parallel system is shown in Figure 10. One method of analyzing non-series-parallel systems uses the following general theorem:

$$R_S(t) = R_S(\text{if } X \text{ is working})\, R_X(t) + R_S(\text{if } X \text{ fails})\, [1 - R_X(t)] \quad (22)$$

The method lies in selecting a critical component (X) and finding the conditional reliability of the system with and without the component working. The theorem on total probability is then used to obtain the systems reliability (see Appendix G).

11. Recommendations

It is recommended that the procedures contained herein be used as guidance for assessing reliability of navigation lock and dam mechanical and electrical equipment. It shall be used to quantify reliability and risk for decision analysis so that upgrade or rehabilitation alternatives can be evaluated.

12. Additional Information

Much of the work covered by this ETL is still under development. The Lock and Dam Equipment Survey Web site and other reliability-related Web sites are listed in Appendix B. The latest information pertaining to the work described herein can be obtained from CECW-EI.

FOR THE DIRECTOR OF CIVIL WORKS:

DWIGHT A. BERANEK, P.E.
Chief, Engineering and Construction Division
Directorate of Civil Works

7 Appendices
APP A - References
APP B - Reliability-Related Internet Web Sites
APP C - Merged Failure Data
APP D - Mechanical Equipment Example
APP E - Electrical Reliability Example
APP F - Example of Lock and Dam Mission Reliability
APP G - Non-Series-Parallel System Analysis

Appendix A: References

A-1. Required Publications

MIL-STD-756B
Reliability Modeling and Prediction

ER 1130-2-500
Project Operations - Partners and Support (Work Management Policies)

EP 1130-2-500
Project Operations - Partners and Support (Work Management Guidance and Procedures)

ETL 1110-2-550
Reliability Analysis of Hydropower Equipment

Mlakar 1994
Mlakar, P. F. 1994. "Reliability of Hydropwer Equipment," Jaycor Report No. J650-94-001/1827, Vicksburg, MS.

A-2. Related Publications

American National Standards Institute/Institute of Electrical and Electronics Engineers 1980
American National Standards Institute/Institute of Electrical and Electronics Engineers. 1980. *Design of Reliable Industrial and Commercial Power Systems.* ANSI/IEEE Std 493-1980, New York.

Bloch and Geitner 1994
Bloch, H. P., and Geitner, F. K. 1994. *Practical Machinery Management for Process Plants, Volume 2, Machinery Failure Analysis and Troubleshooting*, Gulf Publishing, Houston, TX.

Green and Bourne 1972
Green, A. E., and Bourne, A. J. 1972. *Reliability Technology.* Wiley-Interscience, London.

Krishnamoorthi 1992
Krishnamoorthi, K. S. 1992. *Reliability Methods for Engineers,* Quality Press, Milwaukee, WI.

Modarres 1993
Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis*, Marcel Dekker, Inc., New York.

Naval Surface Warfare Center 1992
Naval Surface Warfare Center. 1992. *Handbook of Reliability Prediction Procedures for Mechanical Equipment,* NSWC-92/L01, Carderock Division, Naval Surface Warfare Center, West Bethesda, MD.

Reliability Analysis Center 1995
Reliability Analysis Center. 1995. *Nonelectronic Parts Reliability Data, 1995,* NPRD-95, Reliability Analysis Center, Griffis Air Force Base, Rome, NY.

Sadlon 1993
Sadlon, R. 1993. *Mechanical Applications in Reliability Engineering,* Reliability Analysis Center, Griffis Air Force Base, Rome, NY.

Appendix B : Reliability-Related Internet Web Sites

This appendix lists Internet Web sites that contain information useful to reliability studies:

a. Reliability Analysis Center: http://rac.iitri.org/

b. *Reliability* Magazine: http://www.reliability-magazine.com/index.phtml

c. Reliability Engineering Homepage: http://mijuno.larc.nasa.gov/dfc/releng.html

d. Information Center for Reliability Engineering (University of Maryland): http://www.enre.umd.edu/reinfo.htm

e. Barringer & Associates: http://www.barringer1.com

f. Corps of Engineers Survey of Lock and Dam Mechanical and Electrical Equipment Failures: http://www.mvr.usace.army.mil/failuredata

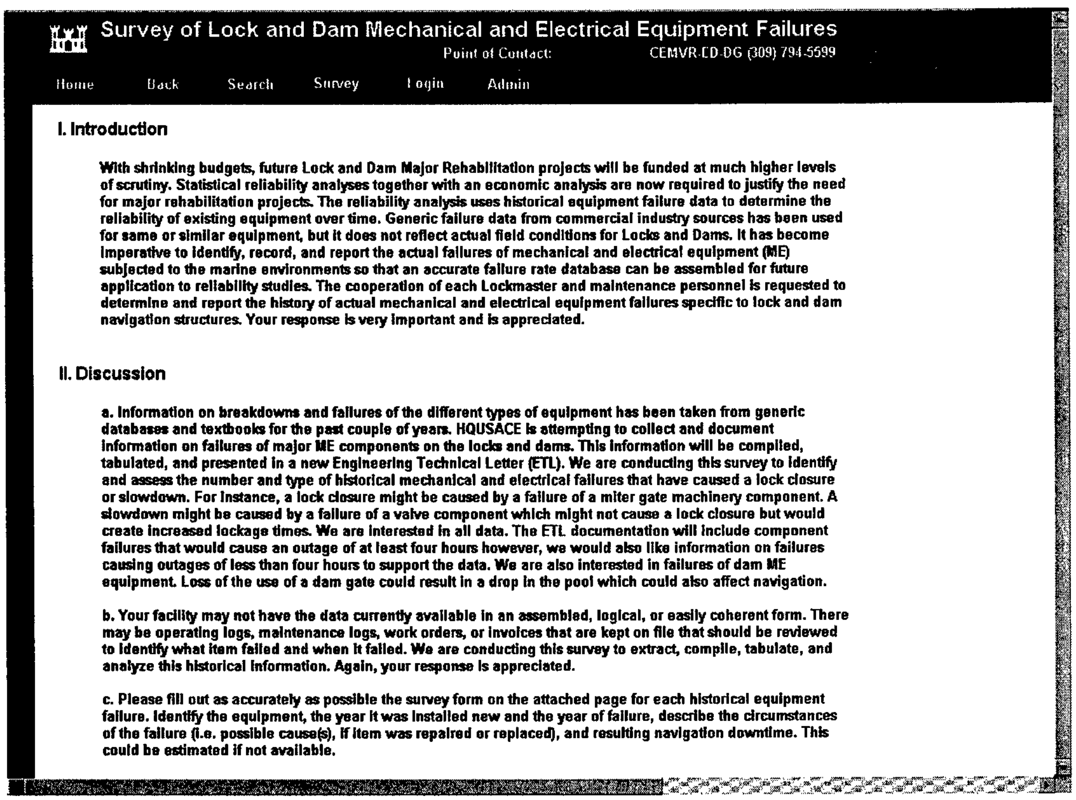
Appendix C: Merged Failure Data

C-1. Description

It is necessary to acquire mechanical and electrical equipment failure data specific to navigation lock and dam equipment to better represent the reliability models. Accumulated data will be analyzed to determine the failure rates that are experienced for applicable mechanical and electrical equipment.

C-2. Equipment Failure Survey

An equipment failure survey Internet Web site was developed as the means to acquire the necessary mechanical and electrical equipment failure data from across the United States. The survey format is currently located on the Internet. The survey Web site homepage is shown in Figure C-1. The survey web page is included in Figure C-2. Survey access may be obtained by logging in and creating an account. The user must create a password when creating the account, and then once the account has been created, the user may log in any time. For each subsequent login, repetitive information will automatically reload, and the user need only input the failure data itself.



Survey of Lock and Dam Mechanical and Electrical Equipment Failures
Point of Contact: CEMVR-ED-DG (309) 794-5599

Home Back Search Survey Login Admin

I. Introduction

With shrinking budgets, future Lock and Dam Major Rehabilitation projects will be funded at much higher levels of scrutiny. Statistical reliability analyses together with an economic analysis are now required to justify the need for major rehabilitation projects. The reliability analysis uses historical equipment failure data to determine the reliability of existing equipment over time. Generic failure data from commercial industry sources has been used for same or similar equipment, but it does not reflect actual field conditions for Locks and Dams. It has become imperative to identify, record, and report the actual failures of mechanical and electrical equipment (ME) subjected to the marine environments so that an accurate failure rate database can be assembled for future application to reliability studies. The cooperation of each Lockmaster and maintenance personnel is requested to determine and report the history of actual mechanical and electrical equipment failures specific to lock and dam navigation structures. Your response is very important and is appreciated.

II. Discussion

a. Information on breakdowns and failures of the different types of equipment has been taken from generic databases and textbooks for the past couple of years. HQUSACE is attempting to collect and document information on failures of major ME components on the locks and dams. This information will be compiled, tabulated, and presented in a new Engineering Technical Letter (ETL). We are conducting this survey to identify and assess the number and type of historical mechanical and electrical failures that have caused a lock closure or slowdown. For instance, a lock closure might be caused by a failure of a miter gate machinery component. A slowdown might be caused by a failure of a valve component which might not cause a lock closure but would create increased lockage times. We are interested in all data. The ETL documentation will include component failures that would cause an outage of at least four hours however, we would also like information on failures causing outages of less than four hours to support the data. We are also interested in failures of dam ME equipment. Loss of the use of a dam gate could result in a drop in the pool which could also affect navigation.

b. Your facility may not have the data currently available in an assembled, logical, or easily coherent form. There may be operating logs, maintenance logs, work orders, or invoices that are kept on file that should be reviewed to identify what item failed and when it failed. We are conducting this survey to extract, compile, tabulate, and analyze this historical information. Again, your response is appreciated.

c. Please fill out as accurately as possible the survey form on the attached page for each historical equipment failure. Identify the equipment, the year it was installed new and the year of failure, describe the circumstances of the failure (i.e. possible cause(s), if item was repaired or replaced), and resulting navigation downtime. This could be estimated if not available.

Figure C-1. Failure Survey Internet Homepage. http://www.mvr.usace.army.mil/failuredata/

MECHANICAL EQUIPMENT

Indicate the main mode of power transfer of the equipment. There may be a combination in types of equipment for a lock. For example, the upper gates may be hydraulic and the lower gates electromechanical. Indicate all that apply.

I. Electromechanical Equipment
An electromechanical system is an electric motor driven gear train system which consists of major components such as gears (open and/or enclosed), shafts, bearings, couplings, brakes.

II. Hydraulic Equipment
A hydraulic system is a fluid power system consisting of cylinders, hydraulic valves (control, relief, etc.), pumps, motors, and piping. The gate installation may include a cylinder connected rack gear that drives a sector gear to move the gate, or the cylinder may be directly connected to the gate.

Type of Gate Operating Machinery: **Edit gate infomation**

Electromechanical Lower, Upper

Type of Valve Operating Machinery: **Edit valve infomation**

Electromechanical Lower, Upper

Edit dam infomation

Type of Dam Operating Machinery:

Electromechanical

Identify Item Of Equipment Or Component That Failed:
Select an item in the list
Insert a different item of equipment or component not listed

Year Component Installed New (Appoximate):

When was failure:

Location of failure:

○ **Gate Machinery** ○ **Valve Machinery** ○ **Dam Machinery** ○ **Other**

Item was:

○ **Repaired** ○ **Replaced**

Describe Known Circumstance(s) Of Failure(i.e. failure mode (fatigue, corrosion, overstress, power surge, etc.)):

(Please limit your entry to 255 characters)

Resulting Navigation Downtime Or Closure If Any (Estimate If Necessary):

Remarks: (Please limit your entry to 255 characters)

Submit

Figure C-2. Mechanical and Electrical Equipment Failure Survey Internet Page

C-3. Processing Data

The accumulated survey information is gathered electronically and stored to a failure database. The failure data entered to date was reviewed and processed for incorporation into this appendix and to provide actual data for mechanical and electrical equipment in use at navigation locks and dams. The database was manually manipulated by the process shown in the flowchart in Figure C-3. It was found during the process that some variations of entries had been entered. Some of the equipment did not apply or there were errors in the entries. Errors or nonapplicable components that were detected were either corrected or the data were not used.

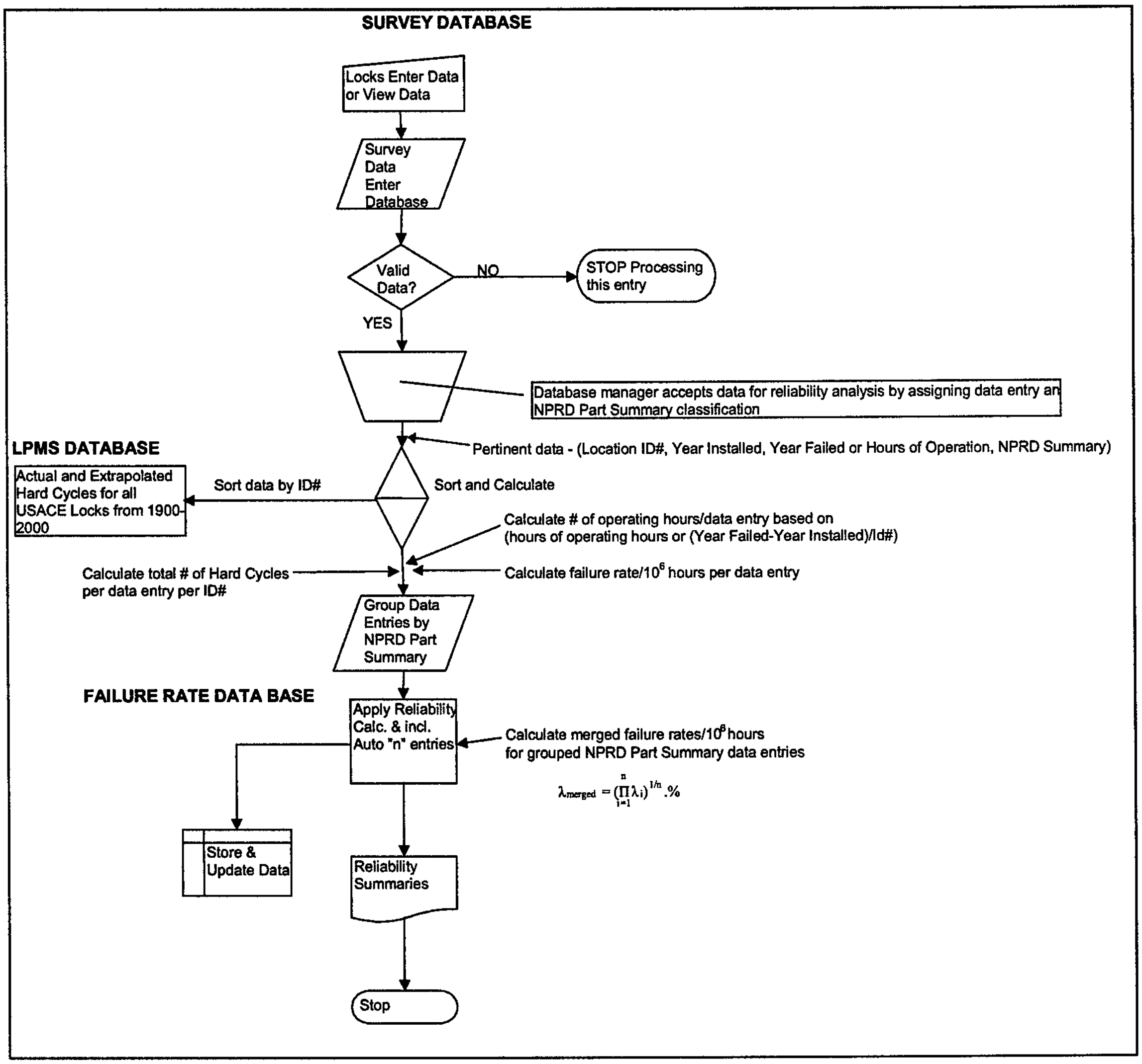


Figure C-3. Failure database analysis flowchart

C-4. Merged Failure Data

The data for individual components were grouped according to methods used and published by the Reliability Analysis Center (1995). The following equation from Reliability Analysis Center (1995) was used to merge the individual failure entries:

$$\lambda_{merged} = \left(\prod_{i=1}^{n} \lambda_i \right)^{1/n} * (\%) \tag{C-1}$$

where

λ_{merged} = a summary failure rate derived from several constituent data source individual failure rates

n = number of records having failures

λ_i = individual failure rate from each source having failures. Individual failure rates were calculated by using a single failure divided by the total number of operating hours for that component

% = percentage of total operating hours associated with data entries having failures to the total operating hours of entries without failures. Percentage for Corps analysis was taken to be 100 percent since all data entries had failures and information related to the overall population and total number of operating hours for the population is unknown

The merged failure data are shown in Table C-1.

CAUTION: The resulting merged failure rates have inherently high variability and more closely represent worst-case failure rates. Real failure rates will be less than those presented. As more data are gathered from occurred failures, the merged failure rates will more closely approximate the real failure data.

Table C-1
Merged Failure Rates

U.S. Army Corps of Engineers Part Summary	Merged Failure Rate per 10^6 Operating Hours	Failures Analyzed
Bearing, Ball, Roller	216.7	5
Bearing, Sleeve	140.9	1
Bolt	69.8	8
Bolt, Anchor	67.8	2
Brake, Electromechanical	289.1	8
Brake, Shoe	3809.0	1
Bus, Connection	374.9	1
Bushing, Cable, Electrical	225.0	1
Bushing, Sleeve	72.4	8
Bushing, Sleeve, Pressed	180.6	1
Cable, Electrical	2482.6	1
Cable, Electrical Lead, Power	47.1	2
Cable, Electrical Lead, Utility 480V	183.6	2
Cable, Wire Rope	228.9	6
Chain, Hoisting, Bicycle Type	70.4	1
Circuit Breaker	127.3	6
Clutch	329.6	1
Clutch, Friction, Power Transmittal	446.4	2
Coil	1624.6	2
Control Assembly, Electrical	70.4	3
Control Panel	117.3	1
Control Panel, Generator	442.1	1
Coupling, Rigid	57.5	1
Coupling, Shaft	75.9	3
Coupling, Tube, Hydraulic	5482.3	2
Drum, Wire Rope	173.6	1
Electrical Motor, AC	296.6	7
Electrical Motor, AC, Starter	234.8	5
Fitting, Hydraulic	1826.2	1
Gauge	123.3	2
Gear Assembly	3809.0	1
Gear, Spur	70.4	1
Hose, Hydraulic	180.6	1
Motor, Selsyn	208.7	4
Nut, Split	2379.1	1
Pin, Mechanical, Gudgeon	94.7	1

(Continued)

Table C-1 (Concluded)

U.S. Army Corps of Engineers Part Summary	Merged Failure Rate per 10^6 Operating Hours	Failures Analyzed
Piston, Hydraulic, Rod	70.7	2
Programmable Logic Controller	216.8	2
Pump, Hydraulic	623.5	3
Receptacle, Electrical	433.4	1
Relay	238.2	3
Relay, Contact, Brake	89.0	1
Relay, Contact, Signal	89.0	1
Roller	122.6	2
Seal	295.5	20
Seal, Oil	149.7	3
Seal, O-Ring	89.0	1
Seal, Packing	94.5	2
Shaft, Power Transmittal	62.6	1
Solenoid, Assembly	125.0	3
Solenoid, Coil	227.8	3
Solenoid, Coil, Brake	60.7	2
Switch	237.8	3
Switch, Control	180.7	6
Switch, Control, Selector	307.9	1
Switch, Interlock	329.6	1
Switch, Limit	405.9	21
Switch, Limit, Rotary	298.1	7
Switch, Micro	142.0	2
Switch, Transfer, Automatic	139.8	4
Tubing, Hydraulic	129.2	2
Valve, Hydraulic, Solenoid	1826.2	1
Valve, Pilot	142.0	1

Appendix D: Mechanical Equipment Example

D-1. Description

For this analysis, the individual mechanical gate systems are considered subsystems to the overall lock and dam system. The example lock miter gate and valve machinery subsystems are laid out as shown in Figures D-1 and D-2. The dam gate machinery is laid out as shown in Figure D-3.

D-2. Reliability Block Diagram Formulation

Formulation of the system reliability block diagram (RBD) is in accordance with MIL-STD-756B. The initial step in determining the reliability of the mechanical systems of the lock and dam is to identify the function or mission of the machinery. The machinery function is to operate the gates. The major components required for mission success are defined and organized into an RBD. The block diagrams for the miter gate and tainter valve and dam gate components included in this evaluation are shown in Figures D-4, D-5, and D-6. The RBD is simplified or expanded, if necessary, to sufficient detail to allow determination of component failure rate from published data. The process continues until only blocks with published component failure rate data remain in the block reliability model. In this example, the structural supports are not included in the model. They are unique to each system, and no published data are available. For the lock and dam gate and valve machinery shown in the figures, the failure of any one component constitutes nonperformance of the mission. There are no parallel or redundant items. The mission and basic block diagrams will be series models.

D-3. Reliability Calculation

The basic and mission reliability model blocks should be keyed with consistent nomenclature of elements. Each model should be capable of being readily updated with new information resulting from relevant tests, as well as any changes in item configuration or operational constraints. Hardware or functional elements of the system not included in the model shall be identified. Rationale for the exclusion of each element from the model shall be provided.

a. Duty cycle. The mission or function of the system should address the duty cycle or period of operation. The miter gate equipment is considered to have a negligible failure rate during periods of non-operation (ignoring barge impact). The failure rate can be modified by a duty cycle factor. The duty cycle factor is the ratio of actual operating time to total mission time t. For example, the equation $R(t) = e^{-\lambda td}$ is the exponential failure rate distribution with a duty factor d. The duty factor for lock mechanical equipment is directly related to the number of lockages or hard operations that occur at a facility. The number of lockages may vary over time, and hence the duty factor may vary. In this example, the lockages or cycles increase with time. The duty factor is calculated for each year as follows: For year 5, the lock performs 11,799 open/close cycles. Assuming the operating time of an open or close operation is 120 seconds (or 240 seconds per open/close cycle) and using a total mission time of 8760 hours per year then,

$$
\begin{aligned}
\text{Operating time} &= (240*11{,}799)/3600 \\
&= 786.6 \text{ operational hours/year} \\
&= 786.6/8760 \text{ hours/year} \\
d &= 0.0898
\end{aligned}
$$

b. Environmental conditions. Environmental conditions shall be defined for the ambient service of the equipment. An approximate approach (Green and Bourne 1972) multiplies failure data by various K

factors to relate the data to other conditions of environment and stress where K is the environmental factor adjustment coefficient used to represent component stress levels altered by environmental conditions. Typical K factors are given in Table D-1 where K_1 relates to the general environment of operation, K_2 to the specific rating or stress of the component, and K_3 to the general effect of temperature. The equipment on the lock is considered to be exposed to an outdoor marine environment. For this example, a K_1 factor of 2 is used and K_2 and K_3 are 1.0.

c. Lock equipment reliability. The Weibull distribution was used to perform the reliability analysis for each component in the block diagram. The values for β were selected from the values given in Table 7-2 of Bloch and Geitner (1994), and reproduced as Table D-2, by choosing a dominant failure mode for each component. If β cannot be determined, a value of 1.0 should be used. It should be noted that most of the β values in Table D-2 are greater than or equal to 1.0, but not greater than 3.0. These values represent random and wear-out failures as indicated by Regions B and C of the bathtub curve. The characteristic life parameter α is determined from the failure rate data. Table D-3 contains failure rates for several common mechanical components found on locks and dams. Appendix C contains a table of failure rate data for lock and dam equipment. This table was generated from data entered in the Web site database for Corps equipment. While α is normally determined through experimental methods, it can be approximated from the ratio of α to Mean Time to Failure (MTTF) as a function of β by using Table D-4. For example, the dominant failure mechanism for the spur gears is considered to be wear such as fretting, scoring, or pitting. From Table D-2, the shape parameter β (Weibull Index) is 3.0, and from Table D-4 α/MTTF = 1.10. The life parameter α is calculated as follows:

(1) Table D-3 was used as the source for the failure rate data. These values are taken from a higher number of sources and have less variability. From the published data of Table D-3, the summary or combined failure rate λ computed from all individual data sources for spur gears is given as 3.2232 failures per million operating hours. The environmental factors are K_1=2, K_2=K_3=1.

(2) The adjusted failure rate λ′ is

$$\lambda' = \lambda K_n \tag{D-1}$$

$$\lambda' = 3.2232 * K_1 * K_2 * K_3 = 6.446 \text{ failures per million operating hours}$$

and

$$\begin{aligned} \text{MTTF} &= 1/\lambda' \\ &= 1/6.446 = 0.155 \times 10^6 \text{ hr} \end{aligned} \tag{D-2}$$

therefore

$$\begin{aligned} \alpha &= \text{MTTF} * 1.1 \\ &= 0.155 \times 10^6 * 1.1 = 0.17 \times 10^6 \text{ hr} \end{aligned} \tag{D-3}$$

$$\alpha = 0.17 \times 10^6/8760 = 19.4 \text{ years}$$

(3) The Weibull reliability function from the main text for the components becomes

$$R(t) = \exp\left[-\left(\frac{td}{\alpha}\right)^{\beta}\right] \tag{D-4}$$

where time t is in years. The Weibull hazard function becomes

$$h(t) = \frac{\beta}{\alpha}\left(\frac{td}{\alpha}\right)^{\beta-1} \tag{D-5}$$

(4) For this example, the electric motors were considered electrical devices and are not included in this reliability analysis. They are evaluated in the electrical analysis. The mechanical system was considered to begin at the first coupling. The reliability for the miter gate machinery model of Figure D-4 at time t is calculated as

$$R_{SYS}(t) = R_A(t)^3 * R_B(t)^2 * R_C(t) * R_D(t) * R_E(t)^2 * R_F(t)^2 * R_G(t)^2 \tag{D-6}$$

(5) The reliability for the tainter valve machinery model of Figure D-5 is calculated as

$$R_{SYS}(t) = R_A(t)^4 * R_B(t)^2 * R_C(t) * R_D(t) * R_E(t)^4 * R_F(t)^3 \tag{D-7}$$

The tainter valve hoist drums and wire rope were not modeled because no failure data were available. Also, these items are organized in parallel so their combined reliability value is much higher than the other components.

d. Dam equipment reliability. The dam machinery block diagram is shown in Figure D-6. The system was considered a series model since the unreliability of one component will cause the entire system to be inoperable. The duty factor for dam equipment is not directly related to the number of lockages. The duty factor was determined as follows:

Assume 2 gate changes per day at 5 min each.

d = (2*5)min/day*365 days/year/60/8760 hrs/year = 0.007

The dam gate system reliability calculation is similar to that for the lock machinery:

$$R_{SYS}(t) = R_A(t) * R_B(t)^{10} * R_C(t) * R_D(t)^4 * R_E(t)^{16} * R_F(t)^6 * R_G(t)^4 \tag{D-8}$$

D-4. Results

a. Lock equipment. The analyses for each major component of the miter gate and tainter valve systems for 50 years of service are contained in spreadsheet format in Tables D-5 and D-6, respectively. The values in the tables are shown rounded to the nearest four decimal places; however, they are not rounded for the mathematical analysis. As a result, some components show a reliability value of 1.0 in future years when their hazard rates are nonzero. The system reliability for the miter gate and valve machinery drops to 41 and 33 percent, respectively, after 50 years. It should be noted that the brakes and the gear reducers have the highest hazard rates, which indicates a higher susceptibility to failure. The electric motors for this analysis were considered electrical equipment and are not included in the mechanical analyses.

b. Dam equipment. The results are tabulated in Table D-7. The dam machinery is 82 percent after 50 years. Because failure data on the sprocket were not available, it was not included in the analysis.

Table D-1
Overall Environment Component Stress Levels (data from Greene and Bourne 1972)

General Environmental Condition	K_1
Ideal, static conditions	0.1
Vibration-free, controlled environment	0.5
General purpose ground based	1.0
Ship	2.0
Road	3.0
Rail	4.0
Air	10.0
Missile	100.0
Stress Rating	
Percentage of component nominal rating	K_2
140	4.0
120	2.0
100	1.0
80	0.6
60	0.3
40	0.2
20	0.1
Temperature	
Component temperature (degrees C)	K_3
0	1.0
20	1.0
40	1.3
60	2.0
80	4.0
100	10.0
120	30.0

Note: Other data sources such as Reliability Analysis Center (1995) also contain environmental information.

Table D-2. Primary Machinery Component Failure Modes (Bloch and Geitner 1994)

Failure Mode	Weibull Index β	Standard Life
Deformation		
Brinelling	1.0	Inf
Cold flow	1.0	Inf
Contracting	2.0	Inf
Creeping	2.0	Inf
Bending	1.0	Inf
Bowing	1.0	Inf
Buckling	1.0	Inf
Bulging	1.0	Inf
Deformation	1.0	Inf
Expanding	1.0	Inf
Extruding	1.0	Inf
Growth	1.0	Inf
Necking	1.0	Inf
Setting	2.0	Inf
Shrinking	2.0	Inf
Swelling	3.0	Inf
Warping	1.0	Inf
Yielding	1.0	Inf
Examples:		
Deformation of springs	1.0	Inf
Extruding of elastomeric seals	1.0	4.0Y
Force-induced deformation	1.0	Inf
Temperature-induced deformation	2.0	Inf
Yielding	1.0	Inf
Fracture/Separation		
Blistering	1.0	Inf
Brittle fracture	1.0	Inf
Checking	1.0	Inf
Chipping	1.0	Inf
Cracking	1.0	Inf
Caustic cracking	1.0	Inf
Ductile rupture	1.0	Inf
Fatigue fracture	1.0	Inf
Flaking	1.0	Inf
Fretting fatigue cracking	1.0	Inf
Heat checking	1.0	Inf
Pitting	1.0	Inf
Spalling	1.0	Inf
Splitting	1.0	Inf
Examples:		
Overload fracture	1.0	Inf
Impact fracture	1.0	Inf
Fatigue fracture	1.1	Inf
Most fractures	1.0	Inf
Change of Material Quality		
Aging	3.0	5.0Y
Burning	1.0	Inf
Degradation	2.0	3.0Y
Deterioration	1.0	Inf
Discoloration	1.0	Inf
Disintegration	1.0	Inf
Embrittlement	1.0	Inf
Hardening	1.0	Inf
Odor	1.0	Inf
Overheating	1.0	Inf
Softening	1.0	Inf

Note: Inf = Infinite
M = Month(s)
Y = Year(s)

(Sheet 1 of 3)

Table D-2 (Continued)

Failure Mode	Weibull Index β	Standard Life
Examples:		
Degradation of mineral oil-based lubricant	3.0	1.5Y
Degradation of coolants	3.0	1.0Y
Elastomer aging	1.0	4.0-16Y
O-Ring deterioration	1.0	2.0-5Y
Aging of metals under thermal stress	3.0	4.0Y
Corrosion		
Exfoliation	3.0	2.0-4.0Y
Fretting corrosion	2.0	3.0Y
General corrosion	2.0	1.0-3.0Y
Intergranular corrosion	2.0	1.0-3.0Y
Pitting corrosion	2.0	1.0-3.0Y
Rusting	2.0	0.5-3.0Y
Staining	2.0	0.5-3.0Y
Examples:		
Accessible Components	2.0	2.0-4.0Y
Inaccessible Components	2.0	2.0-4.0Y
Wear		
Abrasion	3.0	0.5-3.0Y
Cavitation	3.0	0.5-3.0Y
Corrosive wear	3.0	0.5-3.0Y
Cutting	3.0	0.5-3.0Y
Embedding	3.0	0.5-3.0Y
Erosion	3.0	3.0Y
Fretting	3.0	2.0Y
Galling	3.0	2.0Y
Grooving	3.0	2.0Y
Gouging	3.0	2.0Y
Pitting	3.0	1.0Y
Ploughing	3.0	1.0Y
Rubbing	3.0	3.0Y
Scoring	3.0	3.0Y
Scraping	3.0	0.5-3.0Y
Scratching	3.0	3.0Y
Scuffing	3.0	1.0Y
Smearing	3.0	1.0Y
Spalling	3.0	0.5-16Y
Welding	3.0	0.5-3.0Y
Examples:		
Non-lubed relative movement	3.0	1.0Y
Contaminated by lubed sleeve bearings	3.0	3.0M
Spalling of antifriction	3.0	4.0-16Y
Bearings	1.1	16.0Y
Displacement/seizing/adhesion:		
Adhesion	1.0	Inf
Clinging	1.0	Inf
Binding	1.0	Inf
Blocking	1.0	Inf
Cocking	1.0	Inf
Displacement	1.0	Inf
Freezing	1.0	Inf
Jamming	1.0	Inf
Locking	1.0	Inf

(Sheet 2 of 3)

Table D-2 (Concluded)

Failure Mode	**Weibull Index β**	**Standard Life**
Displacement/seizing/adhesion:		
Loosening	1.0	Inf
Misalignment	1.0	Inf
Seizing	1.0	Inf
Setting	1.0	Inf
Sticking	1.0	Inf
Shifting	1.0	Inf
Turning	1.0	Inf
Examples:		
Loosening (locking fasteners)	1.0	Inf
Loosening (bolts)	1.0	Inf
Loosening	1.0	Inf
Misalignment (process pump set)	2.0	1.5-3.0Y
Seizing (linkages)	1.0	Inf
Seizing (components subject to contamination or corrosion)	1.0	Inf
Shifting (unstable design)	1.0	Inf
Leakage:		
Joints with relative movement	1.5	3.0M-4.0Y
Joints without relative movement	1.0	16.0Y
Mechanical seal faces	0.7-1.1	0.5-1.5Y
Contamination		
Clogging	1.0	Inf
Coking	2.0	0.5-3.0Y
Dirt accumulation	2.0	0.5M-3.0Y
Fouling	1.0	Inf
Plugging	1.0	Inf
Examples:		
Fouling gas compressor	3.0	1.5-5.0Y
Plugging of passages with moving medium	1.0	Inf
Plugging of passages with nonmoving medium	1.0	Inf
Conductor Interruption		
Flexible cable	1.0	Inf
Solid cable	1.0	Inf
Burning through Insulation		
Motor windings	1.0	16Y
Transformer windings	1.0	16Y

(Sheet 3 of 3)

Table D-3
Failure Rate Data of Mechanical Components

Component[1]	Failure Rate per 10^6 Operating Hours
Bearings (Summary)	2.9151
Ball (Summary)	1.6445
Roller (Summary)	2.8201
Sleeve (Summary)	2.3811
Couplings, Shaft (Summary)	1.0038
Flexible	1.4054
Rigid	2.6347
Shafts (Summary)	0.9298
Gear Box (Summary)	8.7082
Reducer, Worm	5.0000
Reducer, Spiral Bevel	5.0000
Gear Train (Summary)	3.4382
Gear, Spur	3.2232
Gear, Helical	2.6008
Gear, Worm	3.8258
Gear, Bevel	1.4722
Gear, Rack	1.7562
Brake, Assembly	2.1000
Brake, Electromechanical	10.6383
Hydraulic Cylinder	0.0080
Valves	
Ball (Summary)	0.2286
Butterfly (Summary)	0.2900
Check (Summary)	0.0773
Gate (Summary)	0.0478
Globe (Summary)	0.1439
Hydraulic (Summary)	8.8292
Ball	2.3841
Bellows Diaphragm	14.8953
Check	5.3725
Control	57.7196
Relief	0.9201
Solenoid	25.0590
Seal (Summary)	5.4715
Packing	3.5308
O-ring	4.6511
Gaskets (Summary)	0.0195
Springs (Summary)	0.6134
Pump	
Hydraulic (Summary)	46.9604
Centrifugal	10.4022
Fixed Displacement	1.4641
Positive Displacement	9.5620
Motor Driven	12.9870
Variable Delivery	54.0498
Centrifugal	51.1732
Piping (Summary)	0.4734

[1] Failure rates are from Reliability Analysis Center (1995). The data including the summary data represent combined failure rate data, which is a weighted merger of several failure rates.

Table D-4
α/MTTF Ratio as a function of β (Reliability Analysis Center 1995)

β	α/MTTF
1	1.00
2	1.15
2.5	1.12
3.0	1.10
4.0	1.06

Table D-5
Reliability Analysis, Lock Miter Gate Machinery

Component/Block	Quan.	Failure Rate*	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α, Yrs
Couplings	3	1.4054	misalignment	1.0	1.00	2	40.6131
Antifriction Bearing	2	1.6445	wear	3.0	1.10	2	38.1790
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798
Gear Reducer	1	5.0000	wear	3.0	1.10	2	12.5571
Plain Bronze Bearings	2	2.3811	wear	3.0	1.10	2	26.3682
Spur Gears	2	3.2232	wear	3.0	1.10	2	19.4792
Shafts	2	0.9298	fracture	1.0	1.00	2	61.3870

DUTY FACTOR, d

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Number of Cycles	12758	11799	12336	12514	12692	12841	12991	13249	13508	13754	14000
	0.0971	0.0898	0.0939	0.0953	0.0966	0.0978	0.0989	0.1009	0.1029	0.1047	0.1066

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	1.0000	0.9890	0.9771	0.9654	0.9535	0.9416	0.9295	0.9167	0.9037	0.8904	0.8770
Antifriction Bearings	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9995	0.9992	0.9987	0.9981	0.9973
Brake	1.0000	0.9836	0.9660	0.9488	0.9314	0.9140	0.8966	0.8782	0.8595	0.8408	0.8219
Gear Reducer	1.0000	1.0000	0.9996	0.9985	0.9964	0.9927	0.9869	0.9780	0.9654	0.9485	0.9264
Plain Bronze Bearings	1.0000	1.0000	1.0000	0.9998	0.9996	0.9992	0.9986	0.9976	0.9962	0.9943	0.9918
Spur Gears	1.0000	1.0000	0.9999	0.9996	0.9990	0.9980	0.9965	0.9941	0.9906	0.9859	0.9797
Shafts	1.0000	0.9927	0.9848	0.9770	0.9690	0.9610	0.9528	0.9441	0.9352	0.9261	0.9168

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Antifriction Bearings	0.0000	0.0000	0.0000	0.0001	0.0002	0.0003	0.0005	0.0007	0.0009	0.0012	0.0015
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Gear Reducer	0.0000	0.0003	0.0013	0.0031	0.0057	0.0091	0.0133	0.0189	0.0256	0.0336	0.0430
Plain Bronze Bearings	0.0000	0.0000	0.0001	0.0003	0.0006	0.0010	0.0014	0.0020	0.0028	0.0036	0.0046
Spur Gears	0.0000	0.0001	0.0004	0.0008	0.0015	0.0024	0.0036	0.0051	0.0069	0.0090	0.0115
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM $[R_{sys}(t)]$

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9376	0.8734	0.8127	0.7531	0.6952	0.6382	0.5791	0.5203	0.4624	0.4054

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995)

Table D-6
Reliability Analysis, Lock Tainter Valve Machinery

Component/Block	Quan.	Failure Rate*	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α, Yrs
Couplings	4	1.4054	misalignment	1.0	1.00	2	40.6131
Ball Bearing	2	1.6445	wear	3.0	1.10	2	38.1790
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798
Gear Reducer	1	5.0000	wear	3.0	1.10	2	12.5571
Roller Bearings	4	2.8201	wear	3.0	1.10	2	22.2635
Shafts	3	0.9298	fracture	1.0	1.00	2	61.3870
Wire Rope Drums	2	Information not Available					

DUTY FACTOR, d

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Number of Cycles	12758	11799	12336	12514	12692	12841	12991	13249	13508	13754	14000
	0.0971	0.0898	0.0939	0.0953	0.0966	0.0978	0.0989	0.1009	0.1029	0.1047	0.1066

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	1.0000	0.9890	0.9771	0.9654	0.9535	0.9416	0.9295	0.9167	0.9037	0.8904	0.8770
Ball Bearing	1.0000	1.0000	1.0000	0.9999	0.9999	0.9997	0.9995	0.9992	0.9987	0.9981	0.9973
Brake	1.0000	0.9836	0.9660	0.9488	0.9314	0.9140	0.8966	0.8782	0.8595	0.8408	0.8219
Gear Reducer	1.0000	1.0000	0.9996	0.9985	0.9964	0.9927	0.9869	0.9780	0.9654	0.9485	0.9264
Roller Bearings	1.0000	1.0000	0.9999	0.9997	0.9993	0.9987	0.9976	0.9960	0.9937	0.9906	0.9864
Shafts	1.0000	0.9927	0.9848	0.9770	0.9690	0.9610	0.9528	0.9441	0.9352	0.9261	0.9168

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Ball Bearing	0.0000	0.0000	0.0000	0.0001	0.0002	0.0003	0.0005	0.0007	0.0009	0.0012	0.0015
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Gear Reducer	0.0000	0.0003	0.0013	0.0031	0.0057	0.0091	0.0133	0.0189	0.0256	0.0336	0.0430
Roller Bearings	0.0000	0.0001	0.0002	0.0006	0.0010	0.0016	0.0024	0.0034	0.0046	0.0060	0.0077
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9205	0.8405	0.7666	0.6960	0.6292	0.5655	0.5016	0.4402	0.3820	0.3268

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995)

Table D-7
Reliability Analysis, Dam Gate Machinery

Component/Block	Quan.	Failure Rate*	Failure Mode	Weibull Shape Factor, β	α/MTTF	Environmental K Factor	Charac. Life α,Yrs	Duty Factor, d
Couplings	10	1.4054	misalignment	1.0	1.00	2	40.6131	0.007
Ball Bearing	4	1.6445	wear	1.0	1.00	2	34.7082	0.007
Brake	1	2.1000	jamming/misalign.	1.0	1.00	2	27.1798	0.007
Worm Gear Box	1	5.0000	wear	3.0	1.10	2	12.5571	0.007
Plain Bronze Bearings	16	2.8201	wear	3.0	1.10	2	22.2635	0.007
Spur Gearset	6	3.2232	wear	3.0	1.10	2	19.4792	0.007
Shafts	4	0.9298	fracture	1.0	1.00	2	61.3870	0.007
Sprocket	2	Information not Available						

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50	63
Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
Couplings	1.0000	0.9991	0.9983	0.9974	0.9966	0.9957	0.9948	0.9940	0.9931	0.9923	0.9914	0.9892
Ball Bearing	1.0000	0.9990	0.9980	0.9970	0.9960	0.9950	0.9940	0.9930	0.9920	0.9910	0.9900	0.9874
Brake	1.0000	0.9987	0.9974	0.9961	0.9949	0.9936	0.9923	0.9910	0.9898	0.9885	0.9872	0.9839
Worm Gear Reducer	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Spur Gearset	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Plain Bronze Bearings	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Shafts	1.0000	0.9994	0.9989	0.9983	0.9977	0.9972	0.9966	0.9960	0.9954	0.9949	0.9943	0.9928

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
Couplings	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246	0.0246
Ball Bearing	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288
Brake	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368	0.0368
Worm Gear Reducer	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003
Spur Gearset	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Plain Bronze Bearings	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001
Shafts	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1937	1942	1947	1952	1957	1962	1967	1972	1977	1982	1987	2000
	1.0000	0.9839	0.9681	0.9525	0.9372	0.9221	0.9072	0.8926	0.8782	0.8641	0.8502	0.8149

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995)

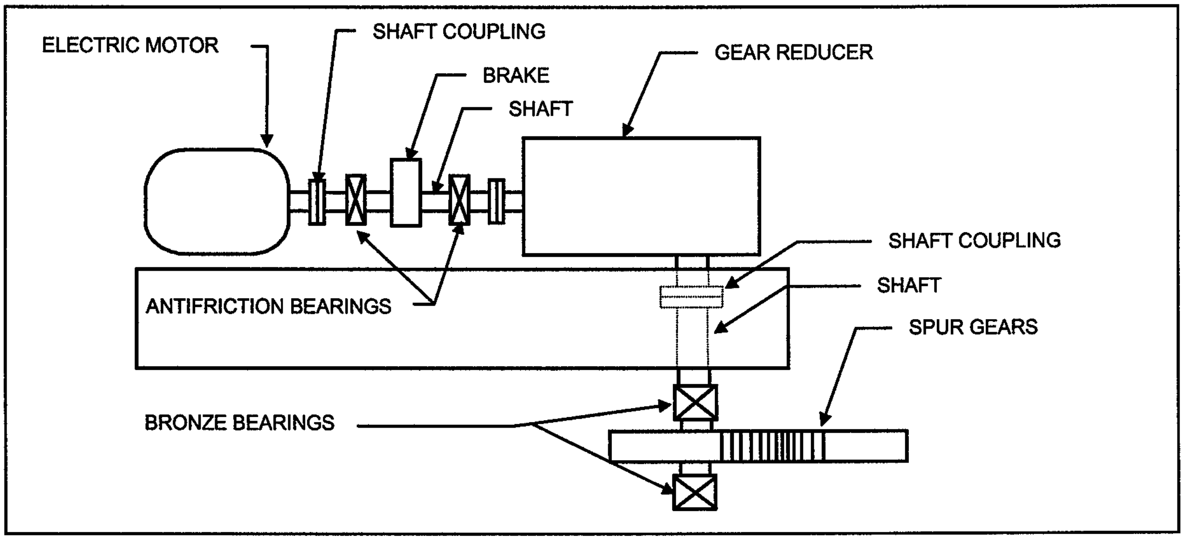


Figure D-1. Miter gate machinery

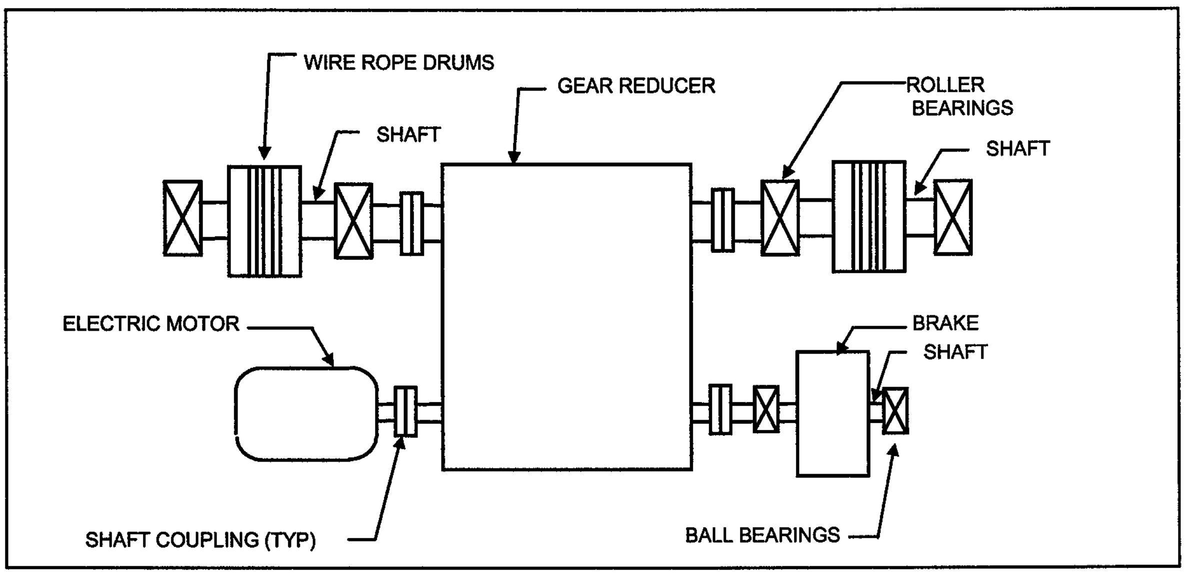


Figure D-2. Tainter valve machinery

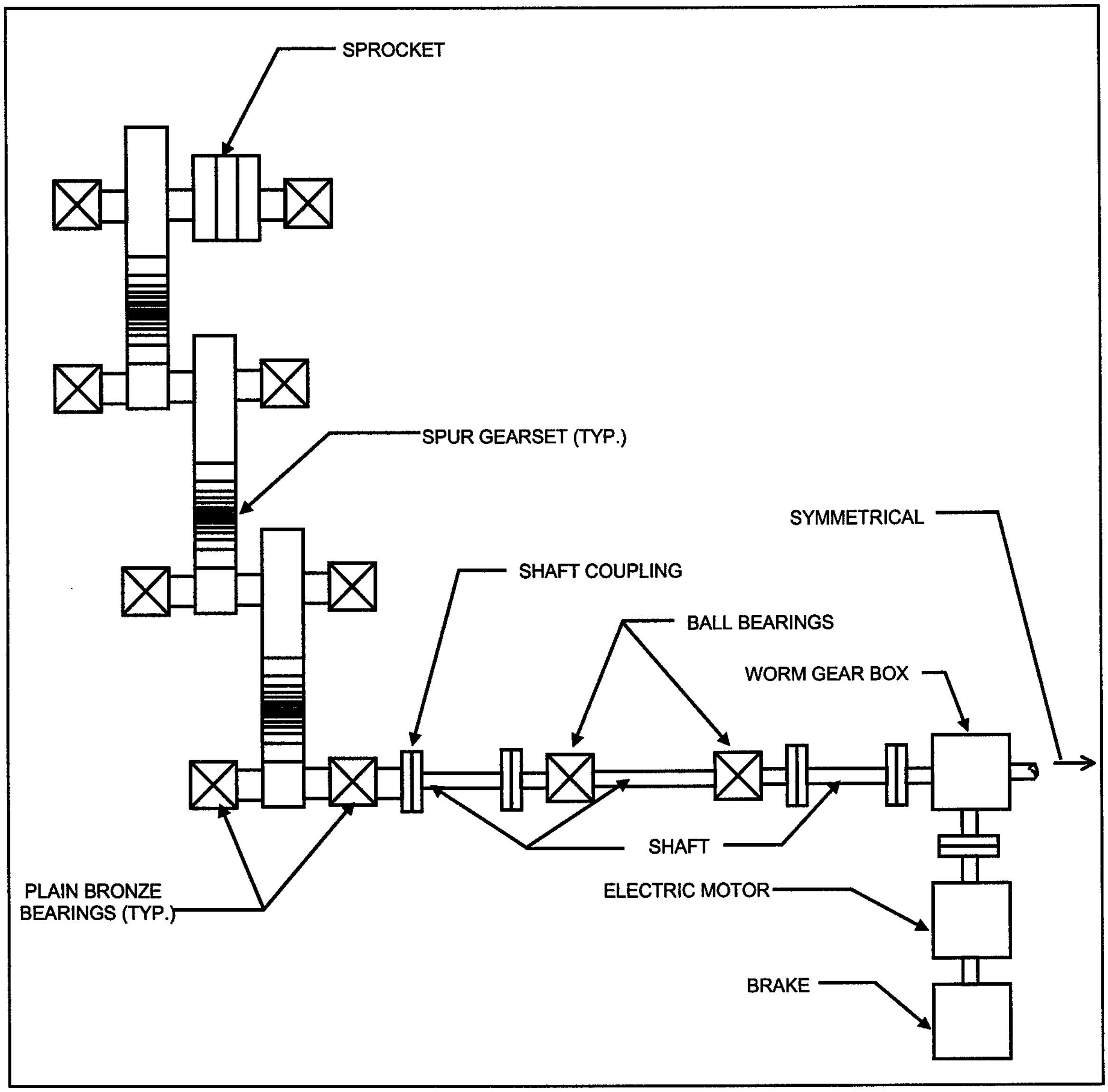


Figure D-3. Dam gate machinery

A - COUPLING
B - ANTIFRICTION BEARING
C - BRAKE
D - GEAR REDUCER
E - PLAIN BRONZE BEARING
F - SPUR GEAR
G - SHAFT

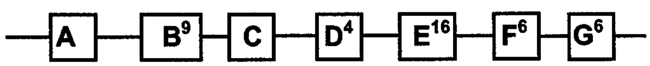
- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts.

Figure D-4. Lock machinery basic and mission reliability diagram

A - SHAFT COUPLING
B - BALL BEARING
C - BRAKE
D - GEAR REDUCER
E - ROLLER BEARING
F - SHAFT

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts, and hoist drums and wire rope.

Figure D-5. Valve machinery basic and mission reliability diagram



A - BRAKE
B - SHAFT COUPLING
C - WORM GEAR BOX
D - BALL BEARINGS
E - PLAIN BRONZE BEARINGS
F - SPUR GEAR SET
G - SHAFTS

- The motor is not included in the analysis.
- Items not evaluated: structural support, various anchor bolts, and chain sprocket.

Figure D-6. Dam machinery basic and mission reliability diagram

Appendix E: Electrical Reliability Example

E-1. Description

The electrical one-line diagram of the example lock and dam electrical system is shown in Figure E-1. The mission reliability electrical subsystems were extracted from Appendix F. Several of the electrical blocks from Appendix F did not have failure rate data readily available. These blocks required further extrapolation to the extent that available failure rate data were available.

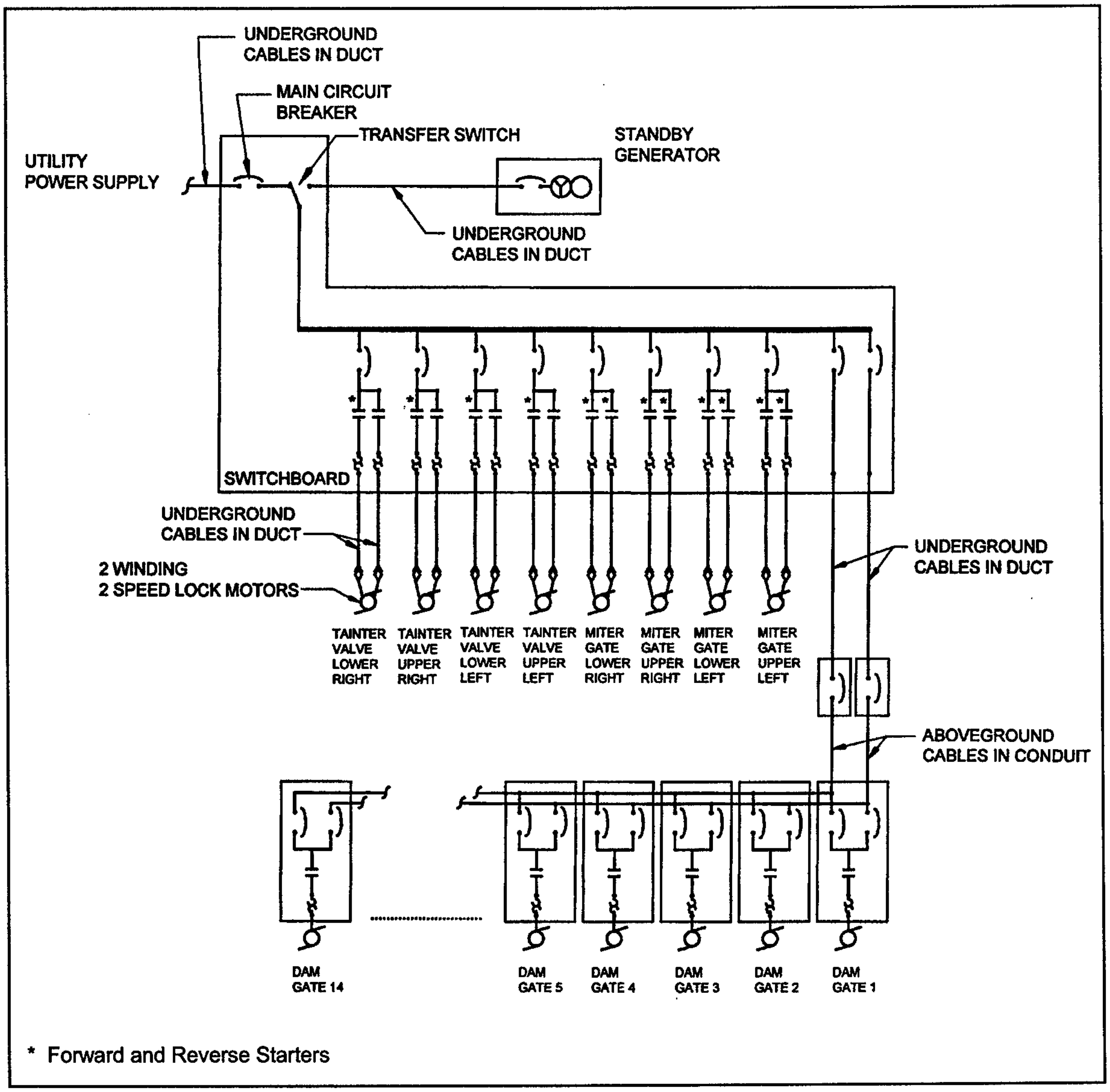


Figure E-1. Lock and dam electrical one-line diagram

E-2. Reliability Block Diagram Formulation

a. The normal electrical service (LAl) was arranged into a series connected block diagram that included the utility power supply, underground cables in duct, and a main circuit breaker as shown in Figure E-2. The resulting equation is

$$R_{SYS}(t) = R_A(t)*R_B(t)*R_C(t) \qquad \text{(E-1)}$$

b. The standby service (LA2) was broken down into a series block diagram of the standby generator and underground cables in duct as shown in Figure E-3. The resulting equation is

$$R_{SYS}(t) = R_D(t)*R_B(t) \qquad \text{(E-2)}$$

c. The automatic transfer switch (LB) and switchboard (LC) did not require additional refinement in the diagram because the reliability information for these items was readily available directly in published sources (Reliability Analysis Center 1995).

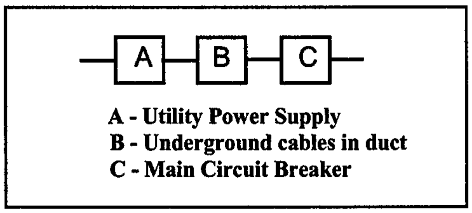


Figure E-2. Electrical service (LA1) block diagram

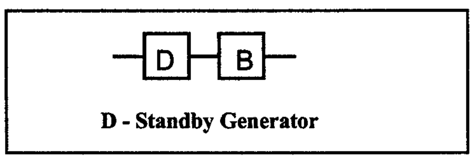


Figure E-3. Standby service (LA2) block diagram

d. The dam feeders and each of the lock gates and valves obtain their power from the switchboard located in the central control station. The two feeder blocks (DD1 and DD2) were connected in parallel to designate the redundancy of this subsystem. Each feeder was diagrammed as a series of blocks representing a molded case circuit breaker, underground cables in duct, another molded case circuit breaker, and aboveground cables in conduit, respectively, as shown in Figure E-4. The resulting equation is

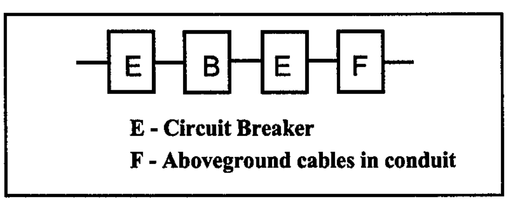


Figure E-4. Dam feeder (DD1 and DD2) block diagram

$$R_{SYS}(t) = R_E(t)*R_B(t)*R_E(t)*R_F(t) \qquad \text{(E-3)}$$

e. Each lock gate (LD1, LD2, LD3, LD4) electrical equipment of Appendix F was extrapolated into appropriate components as a unique parallel-series block diagram. The diagram is shown in Figure E-5. The resulting equation is:

$$R_{SYS}(t) = R_M(t) * (1 - \{1 - [R_N(t) * R_O(t) * R_P(t) * R_Q(t)]\} * \{1 - [R_R(t) * R_S(t) * R_T(t) * R_U(t)]\}) \qquad \text{(E-4)}$$

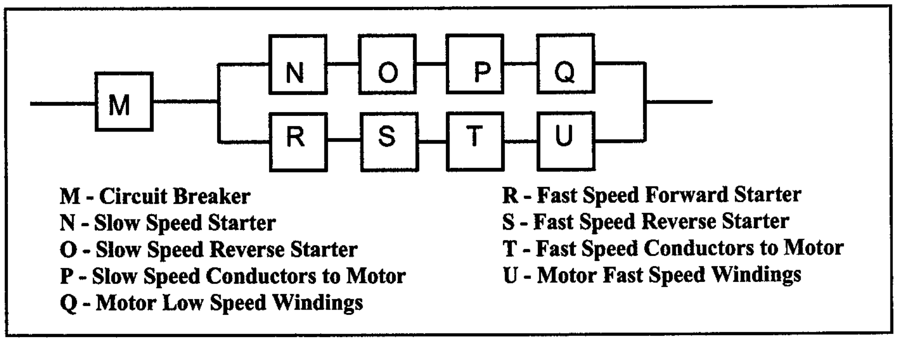


Figure E-5. Lock gate (LD) electrical mission reliability block diagram

f. The lock valve (LE1, LE2, LE3, LE4) electrical equipment was similar except the valves do not have slow speed reverse starter (O) (Figure E-6). The resulting equation is

$$R_{SYS}(t) = R_M(t) * (1 - \{1 - [R_N(t) * R_P(t) * R_Q(t)]\} * \{1 - [R_R(t) * R_S(t) * R_T(t) * R_U(t)]\}) \qquad \text{(E-5)}$$

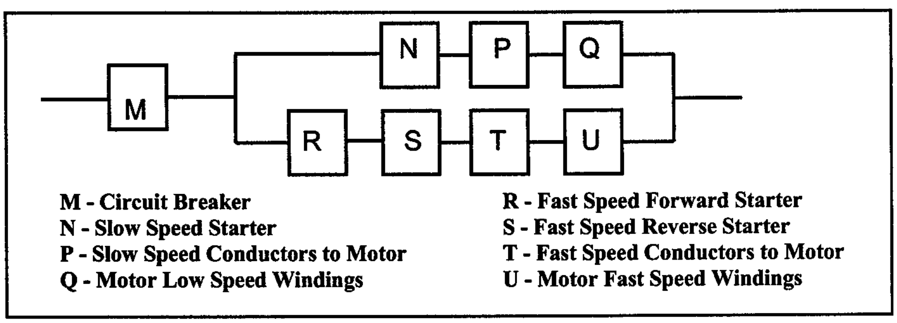


Figure E-6. Lock valve (LE) electrical mission reliability block diagram

g. The dam gate (DE1 through 14) electrical equipment was similar except the gates do not have slow speed starters, conductors, or windings (N, O, P, Q) and have parallel redundant circuit breakers (M) (Figure E-7).

h. The resulting equation is

$$R_{SYS}(t) = \{2*R_M(t)-[R_M(t)*R_M(t)]\}*R_R(t)*R_S(t)*R_T(t)*R_U(t) \qquad \text{(E-6)}$$

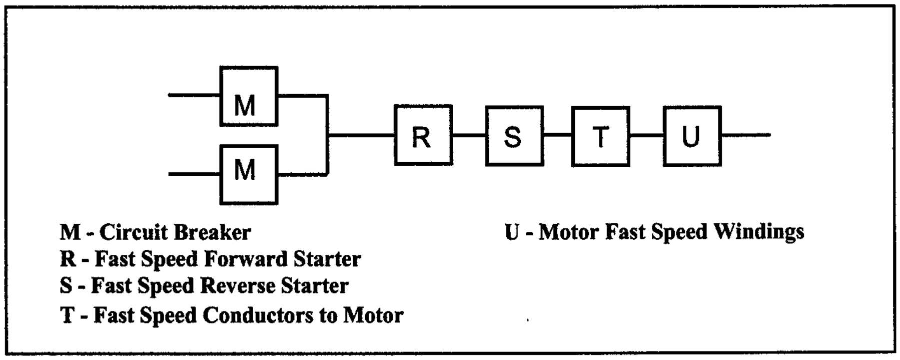


Figure E-7. Dam gate (DE) electrical mission reliability block diagram

E-3. Reliability Calculation

a. Environmental conditions. The environmental conditions were considered for the ambient service of the electrical equipment. Determination of the environmental K factor was the same as for the mechanical equipment (See paragraph D-3*b* and *c*). The electrical equipment on the lock and dam was considered to be exposed to an outdoor marine environment resulting in a K_1 factor of 2.

b. Failure rate. The failure rates of all applicable components were obtained from the published literature of American National Standards Institute/Institute of Electrical and Electronics Engineers (ANSI/IEEE) (1980) and Reliability Analysis Center (1995). Typical component failure rates from these two sources are provided in Tables E-1 and E-2, respectively. The typical failure rates were adjusted in the analysis to the environmental conditions of the lock.

$$\lambda' = \lambda K \tag{E-7}$$

where

λ' = adjusted failure rate

λ = typical failure rate

K = environmental factor = 2

c. Duty cycle.

(1) Failures of electrical equipment often correspond to voltage and/or current parameters. Failure rates are typically provided in "operating hours" or "experience hours," which by definition are a duration of exposure to voltage and/or current. Since voltage and current applied to equipment are near zero when they are not in operation, the total mission time was adjusted with a duty cycle factor. The duty cycle factor is the ratio of actual time the equipment is energized by voltage and/or current to the total mission time t:

$$t' = td \tag{E-8}$$

where

t' = adjusted time variable (i.e., operation time)

t = calendar time variable

d = duty cycle factor

For example, electrical equipment such as transfer switches are normally energized 100 percent of the calendar year resulting in a duty cycle of 1.0. However, the duty factor for lock gate and valve electrical equipment is directly related to the number of lockages or hard operations that occur at a facility. The number of lockages may vary over time, and hence the duty factor may vary. In this example, the lockages or cycles increase with time. The duty factor is calculated for each year as follows: For year 5, the lock performs 11,799 open/close cycles. Assuming the operating time of an open or close operation is 120 sec (or 240 sec for a combined open and close cycle) and using a total mission time of 8,760 hr per year then

Operating time = [(120 * 2) sec/cycle * 11,799 cycles/year] / 3600 sec/hr

= 786.6 operational hr/year

= 786.6/8760 hr/year

d = 0.0898

(2) Each component time variable was adjusted as applicable to its duty cycle. Even though the lock gates and valves are operated with a system duty cycle of 0.0898, the duty cycle for the gate and valve electrical equipment must account for the two-speed operation. The slow speed portion of each system operation is 3 sec/120 sec or 2.5 percent of the system duty cycle. The final duty cycle factor used to adjust the time variable for the slow speed components of the gate and valve equipment was 0.0022, and the associated high-speed factor was 0.0898 - 0.0022 = 0.0876. For forward and reverse starters the applicable duty factor was further reduced by 50 percent to compensate for the alternating use of the starters during a lockage cycle.

(3) The emergency generator duty cycle was calculated assuming a maximum standard operation of 2 hr in 24 hr (0.08). The dam gates were calculated at 0.007 as demonstrated in Appendix D. The dam feeders were calculated at 0.5 using an assumption that each feeder is alternately energized uniformly.

d. Distribution. The modes of failure for electrical equipment are very complex (i.e., they involve a wide variety of distresses such as temperature, vibration, mechanical stresses, etc.) resulting in an inability to select β values for a Weibull distribution. Since the values were not known, a value of 1.0 was used, which reduces the Weibull distribution equation to the exponential distribution for the computation of the reliability value. The exponential reliability equation is

$$R(t) = e^{-\lambda' t'} \quad \text{(E-9)}$$

where

λ' = adjusted failure rate - failures/year

t' = adjusted time variable (operation time) - years

E-4. Results

The results for the electrical subsystems are shown in spreadsheet format in Tables E-3 through E-7. It is evident that the lock electrical distribution reliability is much less than that of any other electrical subsystem evaluated. This was attributed to the 100 percent demand on the major components of that subsystem and also its greater failure rate.

Table E-1
Failure Rate Data of Electrical Components from ANSI/IEEE (1980)

Component (Failures per Unit-Year)	Failure Rate per 10^6 Experience Hours
Electric Utility Power Supplies, Single Circuit (0.537)	61.3014
Transformers	
Liquid Filled, All (0.0041)	0.4680
Dry-Type (0.0036)	0.4110
Generator (Diesel or Gas Driven)	7.6500

Table E-2
Failure Rate Data of Electrical Components from Reliability Analysis Center (1995)

Component[1]	Failure Rate per 10^6 Operating Hours
Arrester, Surge	2.6988
Cable (Summary)	1.1383
Above Ground (in conduit)	0.0300
Above Ground (no conduit)	0.4311
Aerial	0.6516
Below Ground (in duct)	0.5988
Below Ground (in conduit)	0.1876
Below Ground (direct buried)	2.5417
Capacitor Bank	4.5913
Circuit Breaker (Summary)	1.7856
Molded case	0.3574
Electric Motor (Summary)	9.2436
AC	6.8834
DC	14.4367
Fuse (Summary)	2.5012
Receptacle (Summary)	2.2727
Starter (Summary)	0.7636
Motor	0.0212
Switch, Disconnect (Summary)	4.5645
Switchgear (Summary)	0.5830
Bus (Summary)	0.5051
Bare	0.3890
Insulated	0.7925
Switch, Transfer (Summary)	6.3978

[1] The summary data represent combined failure rate data merged from several different sources.

Table E-3
Reliability Analysis, Lock Electrical Distribution

Component/Block	Quan.	Failure Rate*	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Utility Power Supply	1	61.3014	1.0	2	122.6028	1.0000
Conductors in Duct	2	0.5988	1.0	2	1.1976	1.0000
Circuit Breaker	1	0.3574	1.0	2	0.7148	1.0000
Generator	1	7.6500	1.0	2	15.3000	0.0800
Transfer Switch	1	6.3978	1.0	2	12.7956	1.0000
Switchgear, Bus, Bare	1	0.5051	1.0	2	1.0102	1.0000

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Utility Power Supply	1.0000	0.0047	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Conductors in Duct	1.0000	0.9489	0.9004	0.8544	0.8107	0.7693	0.7300	0.6927	0.6573	0.6237	0.5918
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312
Generator	1.0000	0.9478	0.8983	0.8514	0.8070	0.7649	0.7249	0.6871	0.6512	0.6172	0.5850
Transfer Switch	1.0000	0.5710	0.3260	0.1861	0.1063	0.0607	0.0346	0.0198	0.0113	0.0064	0.0037
Switchgear, Bus, Bare	1.0000	0.9567	0.9153	0.8757	0.8378	0.8015	0.7668	0.7336	0.7019	0.6715	0.6424

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Utility Power Supply	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740	1.0740
Conductors in Duct	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Generator	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340	0.1340
Transfer Switch	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121	0.1121
Switchgear, Bus, Bare	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088	0.0088

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.8885	0.7631	0.6566	0.5649	0.4861	0.4182	0.3599	0.3096	0.2664	0.2292

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995) and Appendix A of ANSI/IEEE (1980).

Table E-4
Reliability Analysis, Lock Miter Gate Electrical Equipment

Component/Block	Quan.	Failure Rate*	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate
Circuit Breaker	1	0.3574	1.0	2	0.7148
Forward Starter, Fast	1	0.0212	1.0	2	0.0424
Reverse Starter, Fast	1	0.0212	1.0	2	0.0424
Conductors in Duct, Fast	1	0.5988	1.0	2	1.1976
Electric Motor, AC, Fast	1	6.8834	1.0	2	13.7668
Forward Starter, Slow	1	0.0212	1.0	2	0.0424
Reverse Starter, Slow	1	0.0212	1.0	2	0.0424
Conductors in Duct, Slow	1	0.5988	1.0	2	1.1976
Electric Motor, AC, Slow	1	6.8834	1.0	2	13.7668

DUTY FACTOR, d

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Number of Cycles**	12758	11799	12336	12514	12692	12841	12991	13249	13508	13754	14000
Circuit Breaker	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Forward Starter, Fast	0.0473	0.0438	0.0458	0.0464	0.0471	0.0476	0.0482	0.0492	0.0501	0.0510	0.0519
Reverse Starter, Fast	0.0473	0.0438	0.0458	0.0464	0.0471	0.0476	0.0482	0.0492	0.0501	0.0510	0.0519
Conductors in Duct, Fast	0.0947	0.0875	0.0915	0.0929	0.0942	0.0953	0.0964	0.0983	0.1002	0.1021	0.1039
Electric Motor, AC, Fast	0.0947	0.0875	0.0915	0.0929	0.0942	0.0953	0.0964	0.0983	0.1002	0.1021	0.1039
Forward Starter, Slow	0.0012	0.0011	0.0012	0.0012	0.0012	0.0012	0.0012	0.0013	0.0013	0.0013	0.0013
Reverse Starter, Slow	0.0012	0.0011	0.0012	0.0012	0.0012	0.0012	0.0012	0.0013	0.0013	0.0013	0.0013
Conductors in Duct, Slow	0.0024	0.0022	0.0023	0.0024	0.0024	0.0024	0.0025	0.0025	0.0026	0.0026	0.0027
Electric Motor, AC, Slow	0.0024	0.0022	0.0023	0.0024	0.0024	0.0024	0.0025	0.0025	0.0026	0.0026	0.0027

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312
Forward Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9997	0.9996	0.9995	0.9994	0.9993	0.9991	0.9990
Reverse Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9997	0.9996	0.9995	0.9994	0.9993	0.9991	0.9990
Conductors in Duct, Fast	1.0000	0.9954	0.9904	0.9855	0.9804	0.9753	0.9701	0.9645	0.9588	0.9530	0.9470
Electric Motor, AC, Fast	1.0000	0.9486	0.8955	0.8454	0.7968	0.7503	0.7056	0.6604	0.6166	0.5747	0.5345
Forward Starter, Slow	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Reverse Starter, Slow	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Conductors in Duct, Slow	1.0000	0.9999	0.9998	0.9996	0.9995	0.9994	0.9992	0.9991	0.9989	0.9988	0.9986
Electric Motor, AC, Slow	1.0000	0.9986	0.9972	0.9957	0.9942	0.9927	0.9911	0.9894	0.9877	0.9859	0.9841

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Forward Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Fast	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Fast	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206
Forward Starter, Slow	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter, Slow	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Slow	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Slow	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9691	0.9390	0.9096	0.8811	0.8533	0.8262	0.7998	0.7742	0.7492	0.7249

PROBABILITY OF UNSATISFACTORY PERFORMANCE OF SYSTEM [$1-R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	0.0000	0.0309	0.0610	0.0904	0.1189	0.1467	0.1738	0.2002	0.2258	0.2508	0.2751

HAZARD RATE OF SYSTEM [$h_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
one gate	0.0063	0.0138	0.0215	0.0287	0.0357	0.0423	0.0486	0.0548	0.0609	0.0666	0.0721

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995) and Appendix A of ANSI/IEEE (1980).

** Hard Cycles is approximation based on a linear regression of factual data from the year range of 1980 through 1997.

Table E-5
Reliability Analysis, Lock Tainter Valve Electrical Equipment

Component/Block	Quan.	Failure Rate*	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate
Circuit Breaker	1	0.3574	1.0	2	0.7148
Forward Starter, Fast	1	0.0212	1.0	2	0.0424
Reverse Starter, Fast	1	0.0212	1.0	2	0.0424
Conductors in Duct, Fast	1	0.5988	1.0	2	1.1976
Electric Motor, AC, Fast	1	6.8834	1.0	2	13.7668
Forward Starter, Slow	1	0.0212	1.0	2	0.0424
Conductors in Duct, Slow	1	0.5988	1.0	2	1.1976
Electric Motor, AC, Slow	1	6.8834	1.0	2	13.7668

DUTY FACTOR, d

	Years in Service (Equipment is installed at time 0)										
	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Number of Cycles**	12758	11799	12336	12514	12692	12841	12991	13249	13508	13754	14000
Circuit Breaker	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Forward Starter, Fast	0.0473	0.0438	0.0458	0.0464	0.0471	0.0476	0.0482	0.0492	0.0501	0.0510	0.0519
Reverse Starter, Fast	0.0473	0.0438	0.0458	0.0464	0.0471	0.0476	0.0482	0.0492	0.0501	0.0510	0.0519
Conductors in Duct, Fast	0.0947	0.0875	0.0915	0.0929	0.0942	0.0953	0.0964	0.0983	0.1002	0.1021	0.1039
Electric Motor, AC, Fast	0.0947	0.0875	0.0915	0.0929	0.0942	0.0953	0.0964	0.0983	0.1002	0.1021	0.1039
Forward Starter, Slow	0.0024	0.0022	0.0023	0.0024	0.0024	0.0024	0.0025	0.0025	0.0026	0.0026	0.0027
Conductors in Duct, Slow	0.0024	0.0022	0.0023	0.0024	0.0024	0.0024	0.0025	0.0025	0.0026	0.0026	0.0027
Electric Motor, AC, Slow	0.0024	0.0022	0.0023	0.0024	0.0024	0.0024	0.0025	0.0025	0.0026	0.0026	0.0027

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

	Years in Service (Equipment is installed at time 0)										
	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312
Forward Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9997	0.9996	0.9995	0.9994	0.9993	0.9991	0.9990
Reverse Starter, Fast	1.0000	0.9999	0.9998	0.9997	0.9997	0.9996	0.9995	0.9994	0.9993	0.9991	0.9990
Conductors in Duct, Fast	1.0000	0.9954	0.9904	0.9855	0.9804	0.9753	0.9701	0.9645	0.9588	0.9530	0.9470
Electric Motor, AC, Fast	1.0000	0.9486	0.8955	0.8454	0.7968	0.7503	0.7056	0.6604	0.6166	0.5747	0.5345
Forward Starter, Slow	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Conductors in Duct, Slow	1.0000	0.9999	0.9998	0.9996	0.9995	0.9994	0.9992	0.9991	0.9989	0.9988	0.9986
Electric Motor, AC, Slow	1.0000	0.9986	0.9972	0.9957	0.9942	0.9927	0.9911	0.9894	0.9877	0.9859	0.9841

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Forward Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter, Fast	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Fast	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Fast	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206
Forward Starter, Slow	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Duct, Slow	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Electric Motor, AC, Slow	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9691	0.9390	0.9096	0.8811	0.8533	0.8262	0.7998	0.7742	0.7492	0.7249

PROBABILITY OF UNSATISFACTORY PERFORMANCE OF SYSTEM [$1-R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	0.0000	0.0309	0.0610	0.0904	0.1189	0.1467	0.1738	0.2002	0.2258	0.2508	0.2751

HAZARD RATE OF SYSTEM [$h_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
one valve	0.0063	0.0138	0.0215	0.0287	0.0356	0.0422	0.0484	0.0547	0.0607	0.0665	0.0719

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995) and Appendix A of ANSI/IEEE (1980).

** Hard Cycles is approximation based on a linear regression of factual data from the year range of 1980 through 1997.

Table E-6
Reliability Analysis, Dam Electrical Distribution

Component/Block	Quan.	Failure Rate*	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Circuit Breaker	2	0.3574	1.0	2	0.7148	0.5000
Conductors in Duct	1	0.5988	1.0	2	1.1976	0.5000
Conductors in Conduit	1	0.0300	1.0	2	0.0600	0.5000

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	1.0000	0.9845	0.9692	0.9541	0.9393	0.9247	0.9104	0.8962	0.8823	0.8686	0.8551
Conductors in Duct	1.0000	0.9741	0.9489	0.9243	0.9004	0.8771	0.8544	0.8323	0.8107	0.7897	0.7693
Conductors in Conduit	1.0000	0.9987	0.9974	0.9961	0.9948	0.9935	0.9921	0.9908	0.9895	0.9882	0.9869

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Conductors in Duct	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105	0.0105
Conductors in Conduit	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005

RELIABILITY OF SYSTEM [$R_{sys}(t)$]

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040
	1.0000	0.9428	0.8890	0.8382	0.7903	0.7451	0.7025	0.6624	0.6245	0.5888	0.5552

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995) and Appendix A of ANSI/IEEE (1980).

Table E-7
Reliability Analysis, Dam Gate Electrical Equipment

Component/Block	Quan.	Failure Rate*	Weibull Shape Factor, β	Environmental K Factor	Adjusted Failure Rate	Duty Factor, d
Circuit Breaker	2	0.3574	1.0	2	0.7148	1.0000
Forward Starter	1	0.0212	1.0	2	0.0424	0.0035
Reverse Starter	1	0.0212	1.0	2	0.0424	0.0035
Conductors in Conduit	1	0.0300	1.0	2	0.0600	0.0070
Electric Motor, AC	1	6.8834	1.0	2	13.7668	0.0070

RELIABILITY [R(t)] OF INDIVIDUAL COMPONENTS

Years in Service (Equipment is installed at time 0)

	0	5	10	15	20	25	30	35	40	45	50	63
Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2053
Circuit Breaker	1.0000	0.9692	0.9393	0.9104	0.8823	0.8551	0.8287	0.8032	0.7784	0.7544	0.7312	0.6740
Forward Starter	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
Reverse Starter	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
Conductors in Conduit	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9998	0.9998	0.9998
Electric Motor, AC	1.0000	0.9958	0.9916	0.9874	0.9833	0.9791	0.9750	0.9709	0.9668	0.9627	0.9587	0.9482

HAZARD RATES [h(t)] OF INDIVIDUAL COMPONENTS

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2053
Circuit Breaker	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063	0.0063
Forward Starter	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Reverse Starter	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
Conductors in Conduit	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Electric Motor, AC	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206	0.1206

RELIABILITY OF SYSTEM $[R_{sys}(t)]$

Year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2053
	1.0000	0.9948	0.9879	0.9794	0.9695	0.9584	0.9462	0.9331	0.9191	0.9044	0.8891	0.8471

* Failure Rate per 10^6 Operating Hours from Reliability Analysis Center (1995) and Appendix A of ANSI/IEEE (1980).

Appendix G: Non-Series-Parallel System Analysis

A complex system that is neither in series nor parallel is shown in Figure G-1. The reliability is evaluated using the theorem on total probability:

$$R_S(t) = R_S(\text{if } X \text{ is working})\, R_X(t) + R_S(\text{if } X \text{ fails})\, (1 - R_X(t)) \tag{G-1}$$

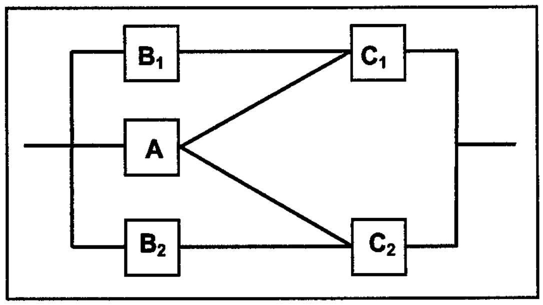


Figure G-1. A non-series-parallel system

Select a critical component. In this case, select component A. The system can function with or without it, and in each case the system resolves into a simpler system that is easily analyzed. If A works, it does not matter if B_1 or B_2 is working. The system can then be represented by the reliability block diagram in Figure G-2.

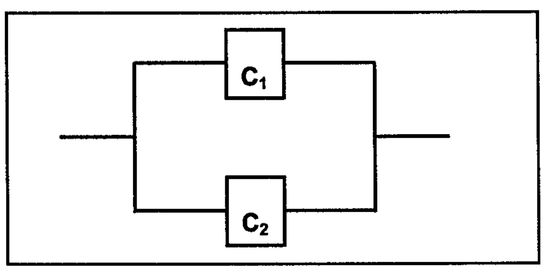


Figure G-2. Reduction of system with component A working

If component A does not work, the system can be reduced to Figure G-3.

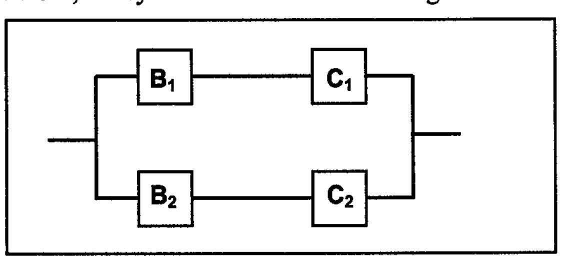


Figure G-3. Reduction of system with component A not working

Figure G-2 is evaluated as follows:

$$R_S(\text{if } A \text{ is working}) = 1 - \{[1 - R_{C1}(t)][1 - R_{C2}(t)]\} \tag{G-2}$$

Figure G-3 is resolved as

$$R_S(\textit{if A fails}) = 1 - (\{1 - [R_{B1}(t) * R_{C1}(t)]\}\ \{1 - [R_{B2}(t) * R_{C2}(t)]\}) \qquad \text{(G-3)}$$

The total system reliability becomes

$$R_S(t) = R_S(\textit{if A is working})\ R_A(t) + R_S(\textit{if A fails})\ [1 - R_A(t)] \qquad \text{(G-4)}$$